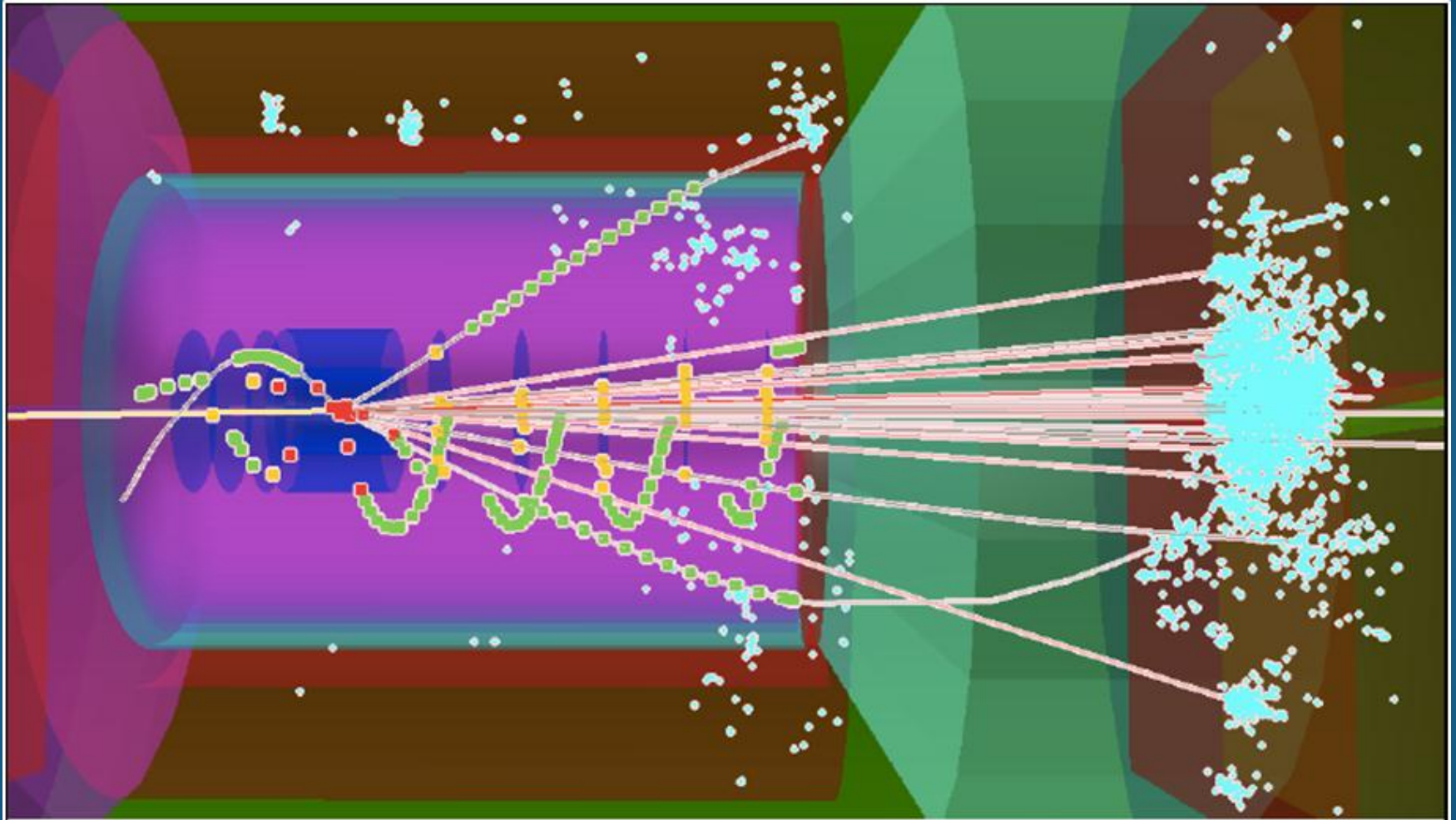


# RD6 – Tracking Consortium



T.K. Hemmick

# Outline

- Detector Research Goals:
  - Central Arm: TPC+HBD combined detector.
  - Forward Endcaps:
    - Planar GEM detectors
      - Large area
      - Possibly providing a vector-stub
    - CsI photocathode RICH.
      - CsI cathode technology well known.
      - Large area mirror development is current focus of R&D.
- Broader Program Impact:
  - Participated in organizing simulation workshop.
  - Holding joint meetings with Calorimeter Group.

# Collaboration Status

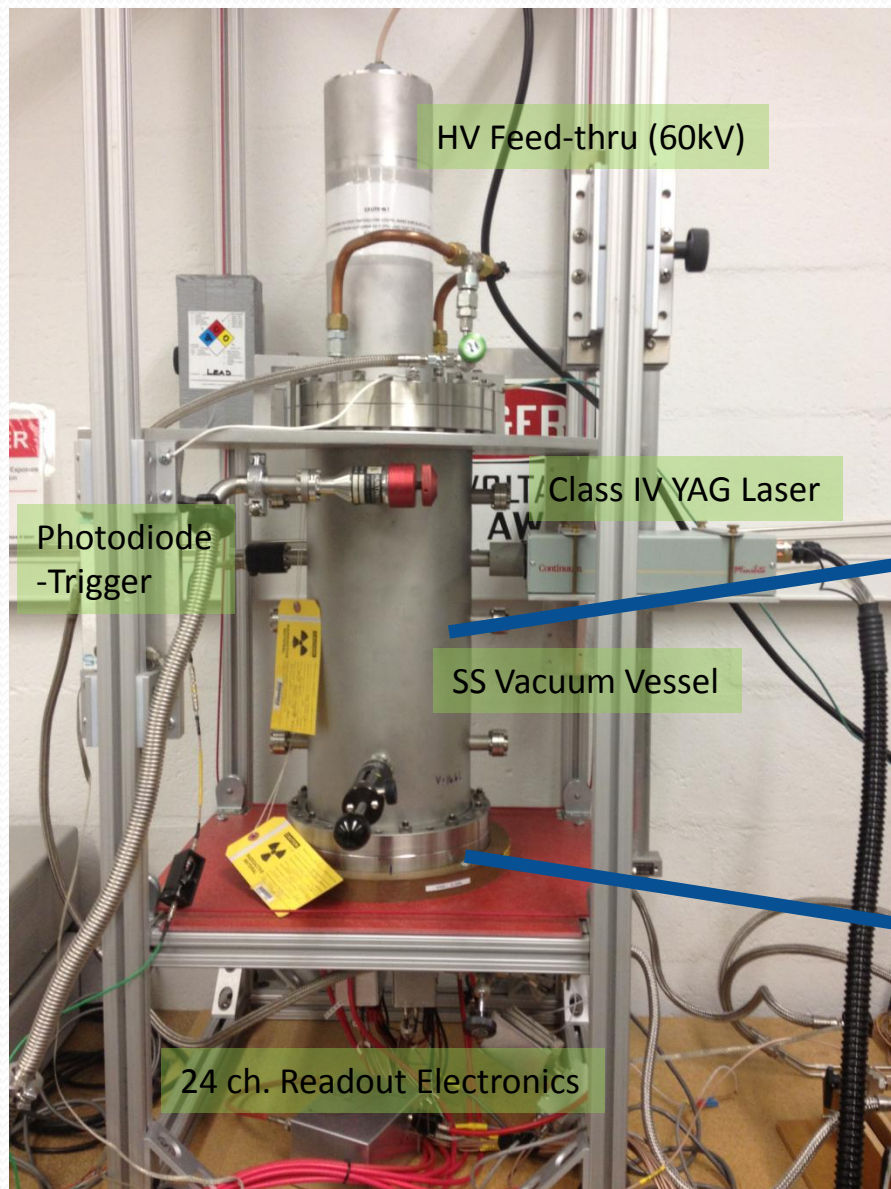
- Funding cycle from May 2012 “straddled” fiscal year.
- Strategy for first funding portion:
  - Fully fund hardware postdoc.
  - Minimally fund ongoing hardware efforts.
- Search Results Excellent!:
  - 17 applications.
  - 3 selected for interview.
  - Decision process ongoing.
- Further development:
  - Nils Feege hired to spin group @ SBU.
  - Recently arrived and will dedicate major effort to EIC.

# CENTRAL ARM: Fast TPC with RICH PID

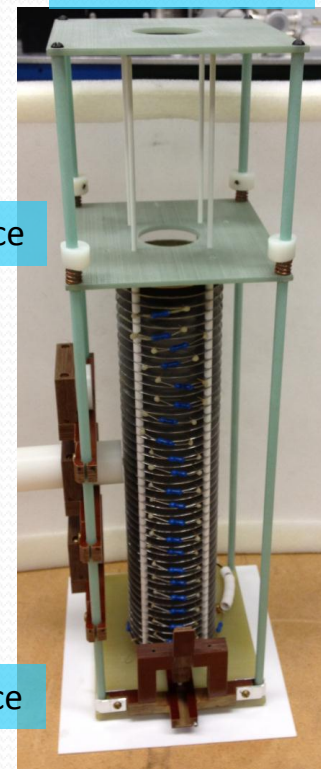
- Studies have begun to investigate TPC/RICH gas mixtures
  - TPC test setup now up and running at BNL
    - required resurrecting laser, HV supply, safety approvals, etc.
  - Started measuring charge attachment, gas transmission, etc
- Started designing first small prototype detector using 10x10 cm<sup>2</sup> GEMs
  - Preliminary field cage design
    - will need more sophisticated electrostatic program in the future
  - Started mechanical design
  - Acquired readout electronics from STAR Forward TPC
    - looking at other readout electronics from PANDA and ILC groups
- Hope to have a prototype detector w/readout system ready for a beam test in the second half of 2013



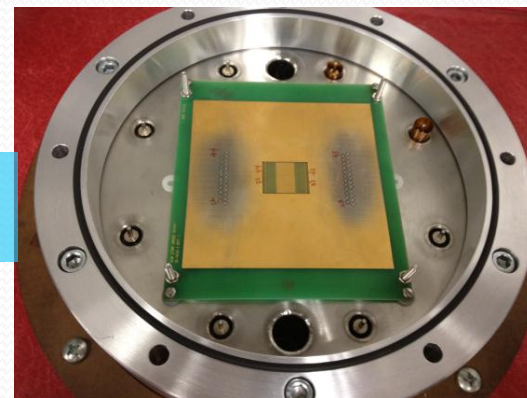
# TPC Test Set Up



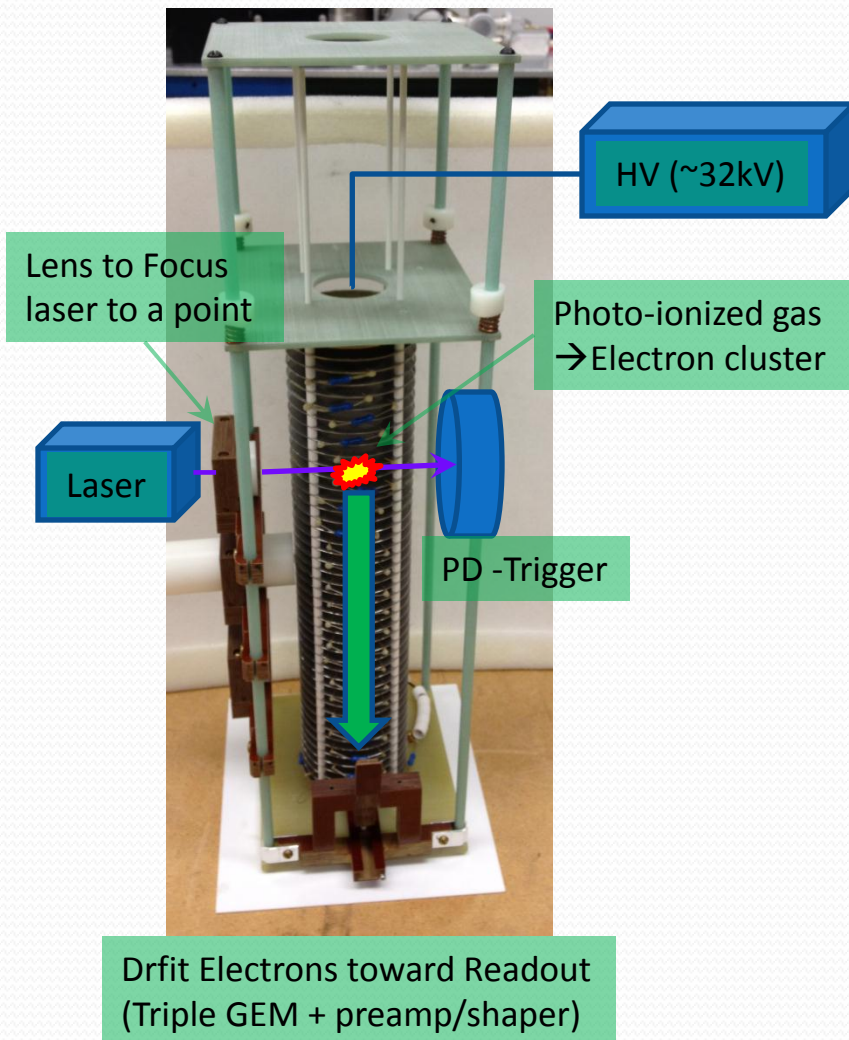
32cm Drift Cell



10x0.3mm pad  
Readout (24ch.)

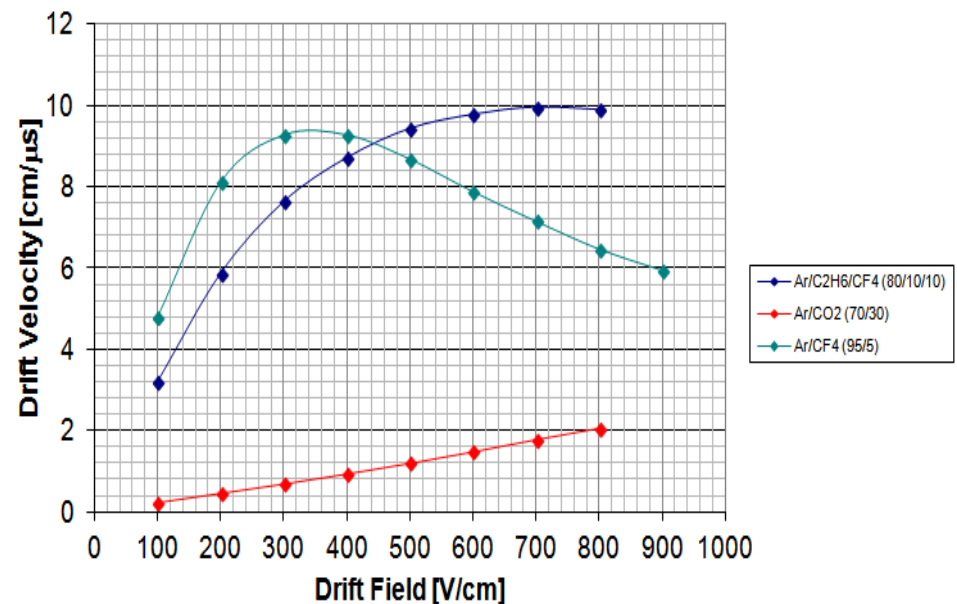


# Drift Velocity Measurements



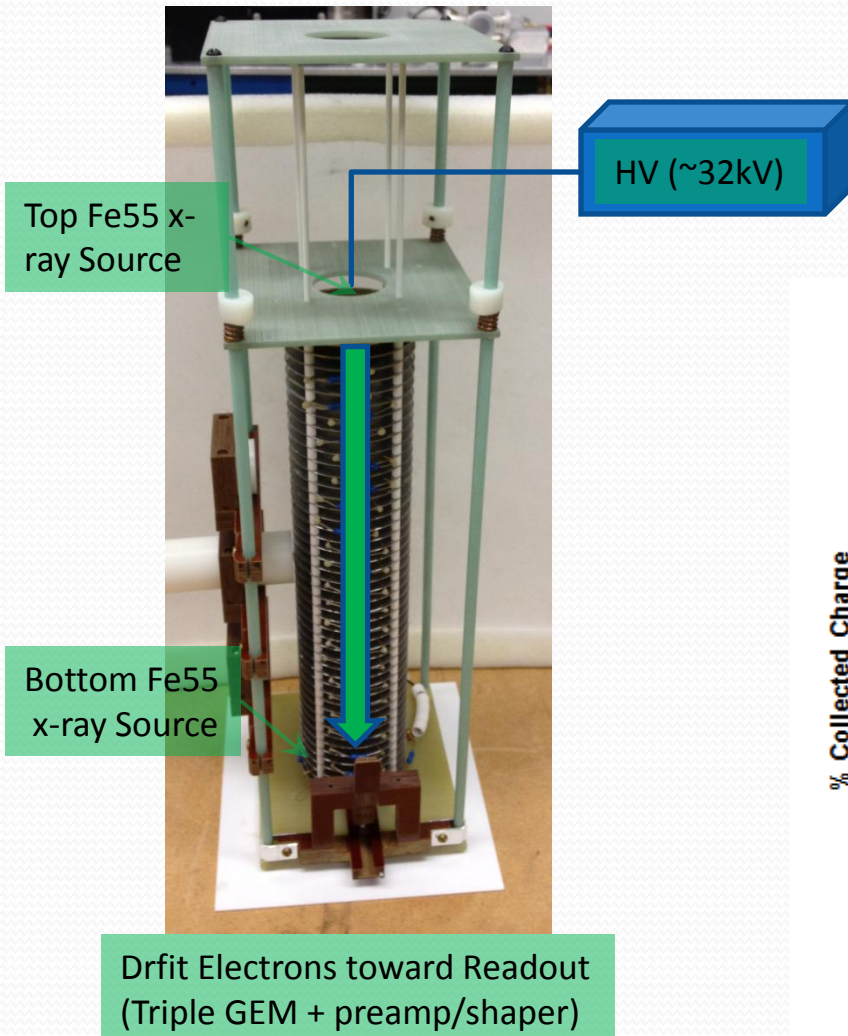
- The PD provides a trigger at the time the laser produces the cluster of electrons.
- The drift time is then measured as the arrival time of the charge cluster at the readout.

**Electron Drift Velocities in Various Gas Mixtures**

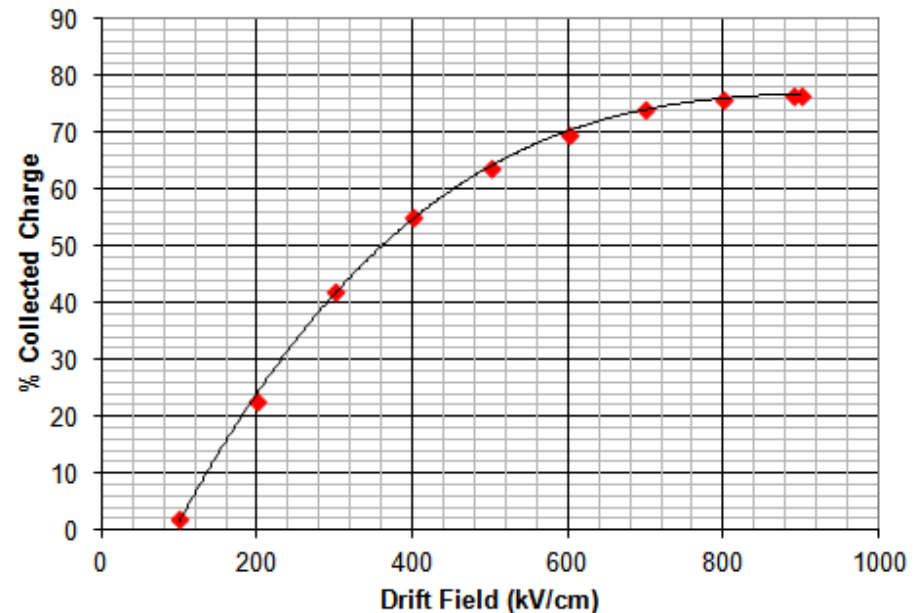


# Charge Attachment Measurements

- As electron clusters produced by the top Fe55 source drift toward the readout, they lose charge due to charge loss mechanisms within the gas.
- The amount of lost charge may be measured by taking the ratio of the total charge measured at the readout from the top source ( $\sim 32\text{cm}$  drift) and the total charge measured from the bottom source ( $\sim 0\text{cm}$  drift).

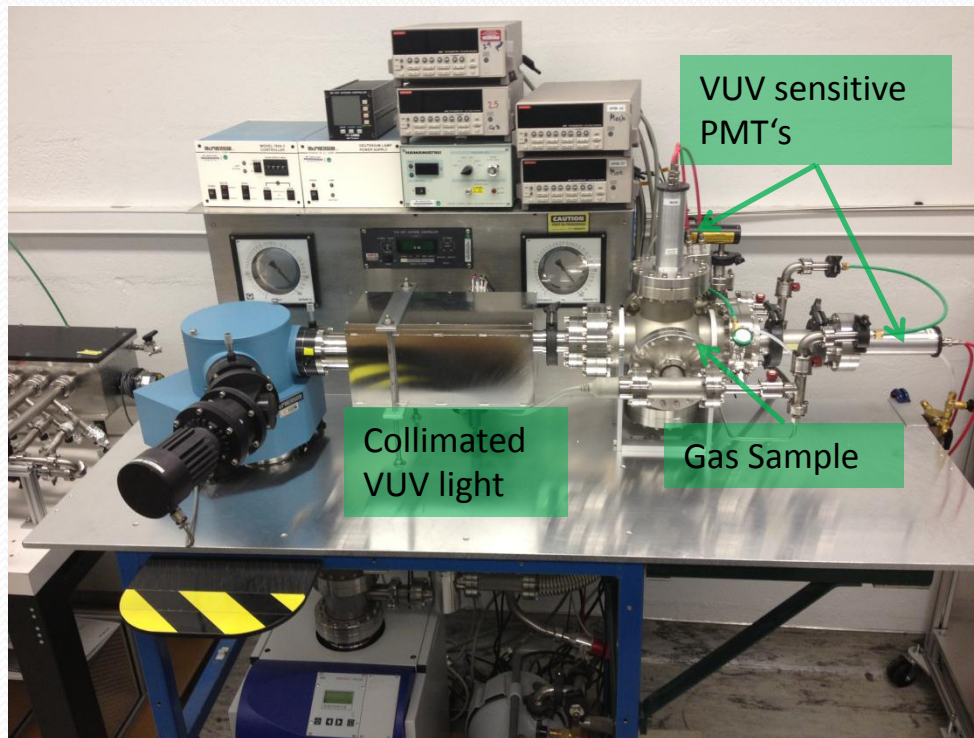


**Charge attachment after 32cm drift in  
 $\text{ArCo}_2$  (70/30)**

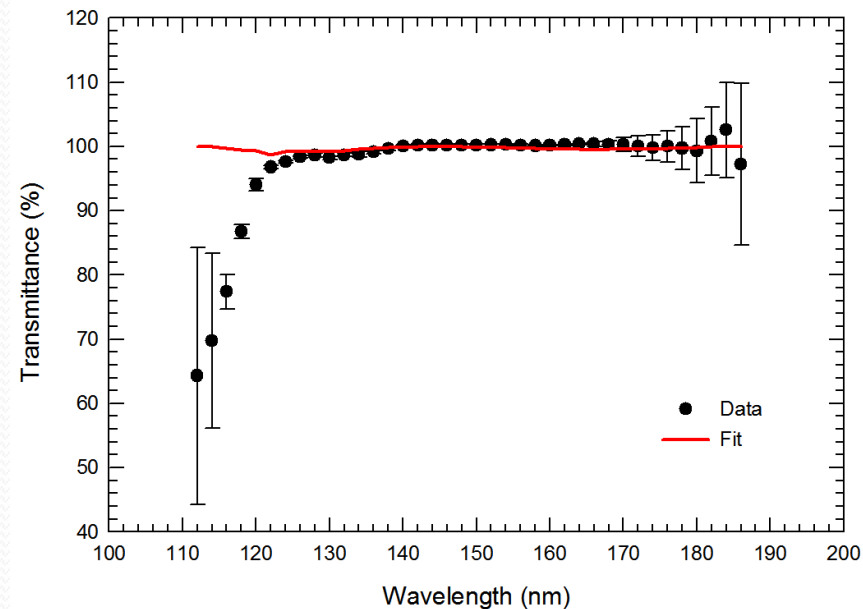




# Gas Transmittance Measurements

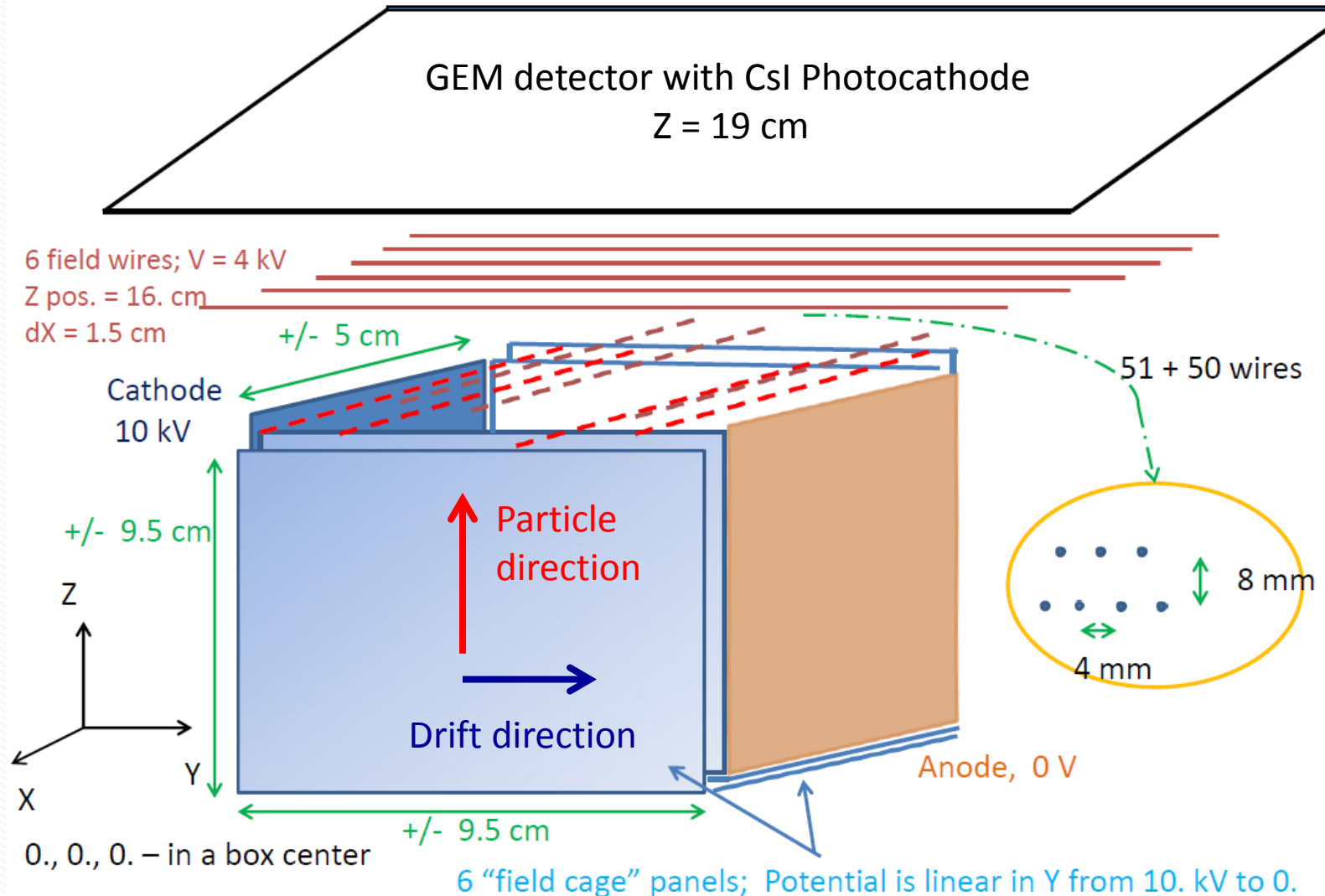


Transmittance of pure CF<sub>4</sub>

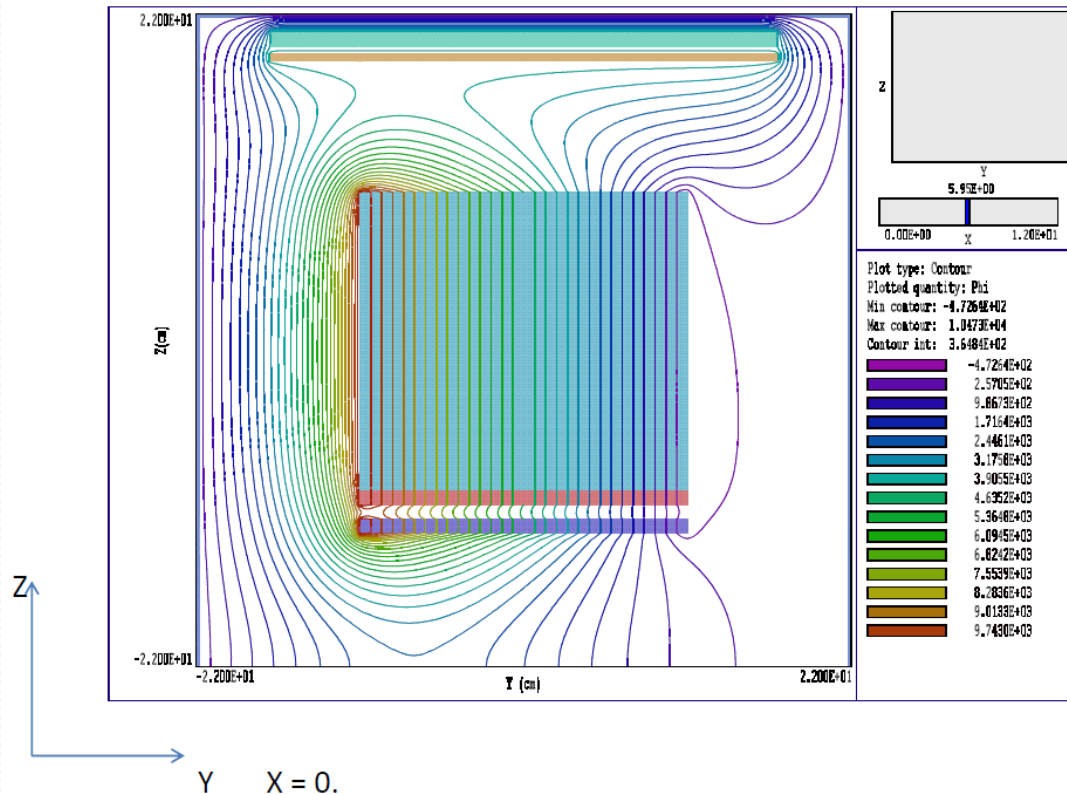


We have the ability to measure the transmittance of various gases within the lab, which is necessary for studying drift gases that must also be transparent to Cherenkov photons.

# Prototype TPC/RICH Detector Design



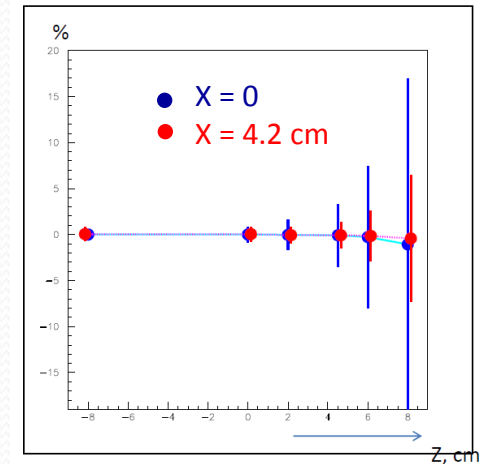
# Prototype TPC/RICH Field Cage Simulation



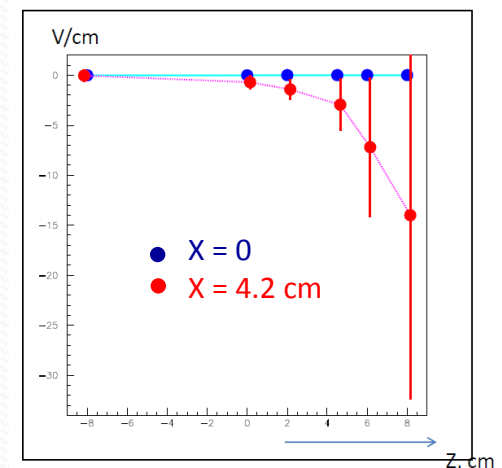
Electrostatic simulations done with Amaze 2.0 + HiPhi 2.5

- Free, but very limited in terms of capabilities, resolution, etc
- Need to use more sophisticated program (e.g., 3D Maxwell, Garfield, etc) in the future

$(E_y / \langle E_y \rangle - 1) (\%)$



$(E_x \text{ (V/cm)})$



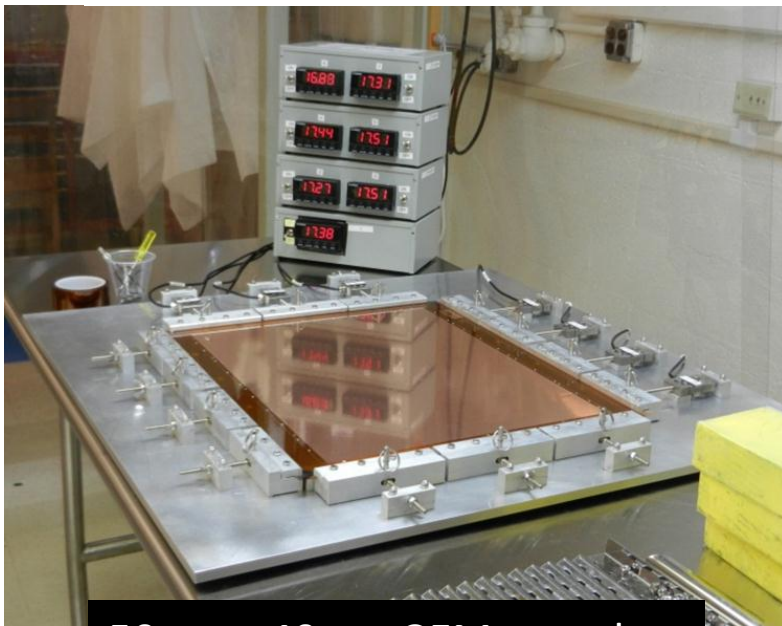


# Forward Endcap:

- Principle Tracking Issues:
  - Size of GEM frames and mechanical details.
    - V-shaped “octagonal” sector.
    - Development of S4 tensioning scheme.
  - Gas volume.
    - Development of vectoring using extended drift gap.
  - Readout Options.
    - Diagonal strips.
    - Zig-zag
    - 3-coordinate.
- Principle low-n cherenkov issues
  - In-house mirror development

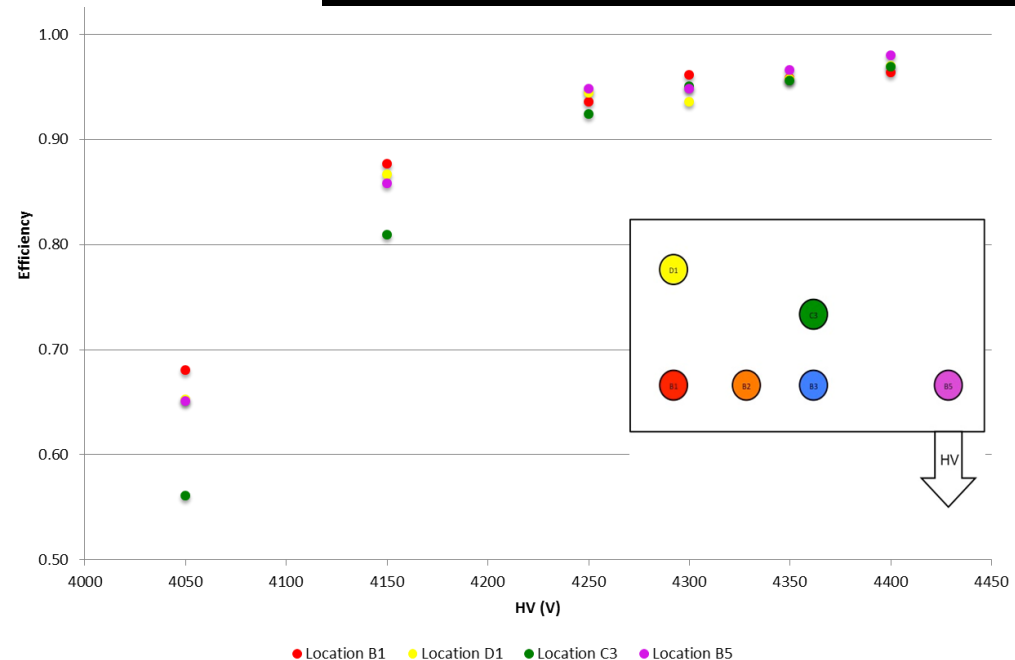
# University of Virginia EIC detector R&D Status

- Successfully constructed and tested a midsize (50 cm x 40 cm) prototype GEM that contains the features planned for the UVa EIC GEM module.
  - Stretching technique worked well; optimum tension found.
  - module with narrow edges holds tension well, no foil or chamber deformation under tension.
  - GEM chamber works well, under testing now.
  - One problem discovered: metal dust from stretcher screws contaminating the chamber. The solution: fabricate stretcher part out of hard plastic.
- The design of the UVa EIC GEM module is complete. The GEM foil orders have been placed.
- The design of the 2D readout board is underway.



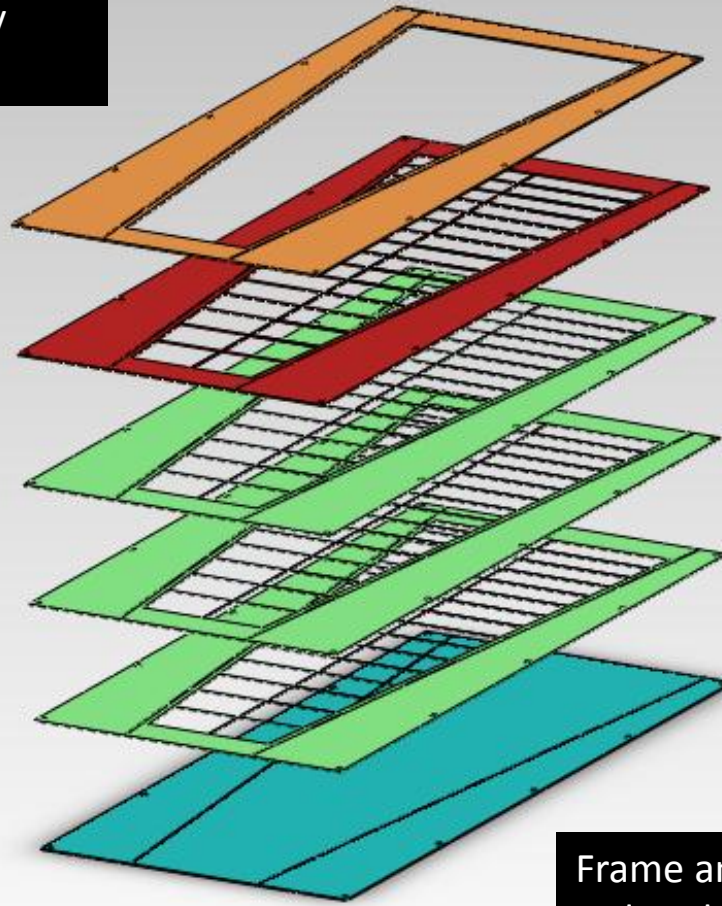
50 cm x 40 cm GEM stretcher

40 x 50 GEM module efficiency as a function of position and high voltage



# UVa EIC GEM module frame design

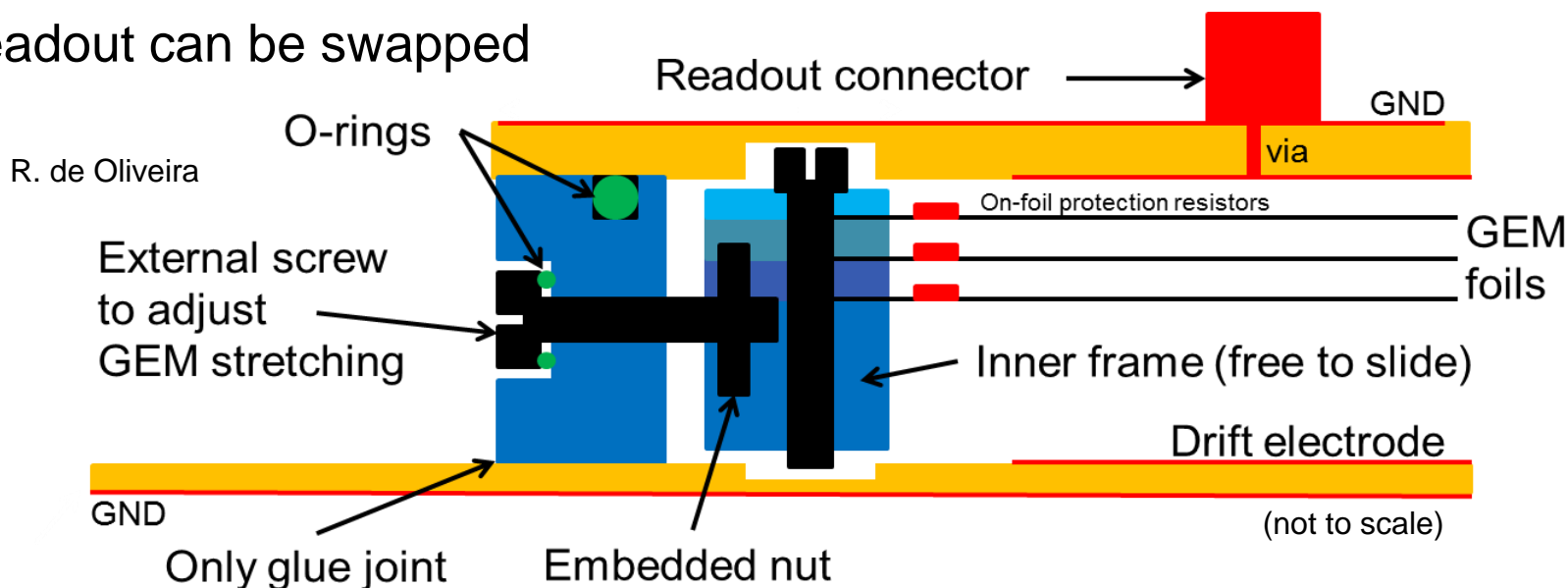
The “wings” on each plane are for support during assembly. These will be removed once the chamber is fully assembled, leaving 8 mm sides.



Frame and foil design is complete;  
order placed with CERN GEM  
workshop.

- Simplified “S4 (**self-stretched, sans spacer**)” construction

- self-stretched: No more gluing of GEM foils onto spacer frames
- sans spacer: No more spacers inside active volume
- Readout can be swapped

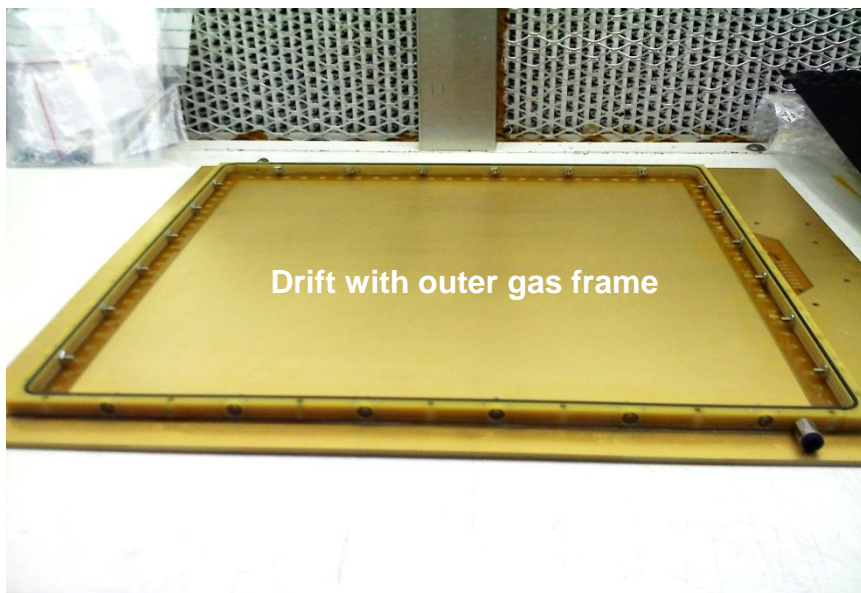


- The parts for a 30cm × 30cm Triple-GEM were procured from CERN (Rui de Oliveira) using funds from this project
- Detector was built in a cleanroom flow hood by a student, who systematically recorded issues encountered with construction

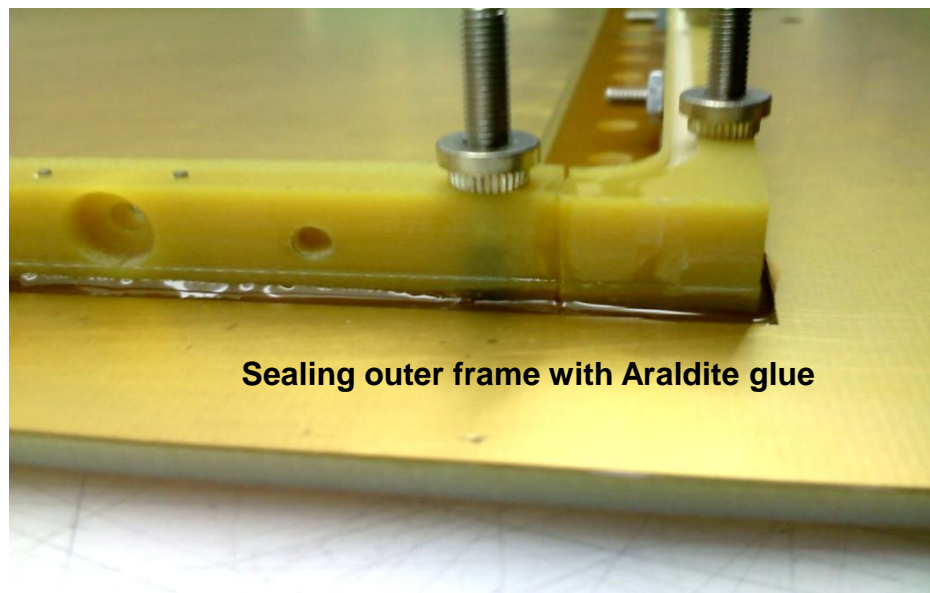


$E_{IC}$

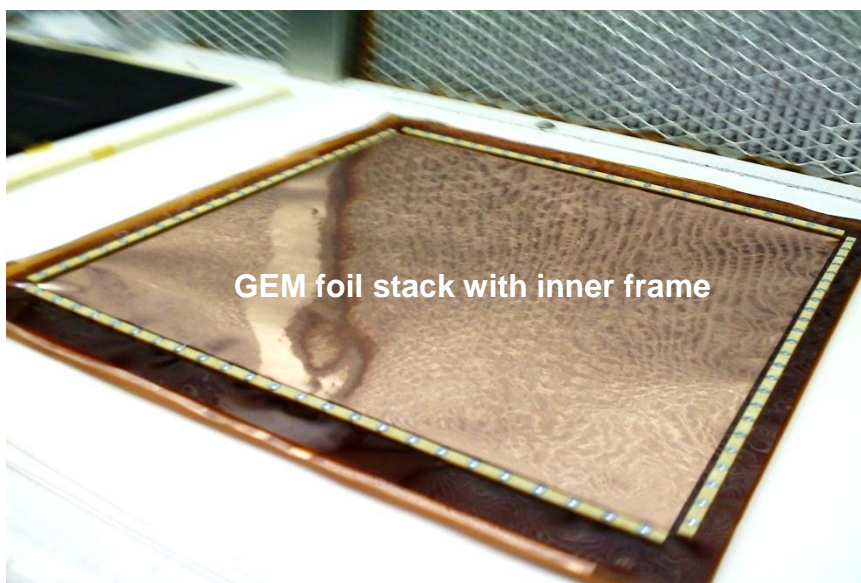
# 30cm × 30cm S4 GEM



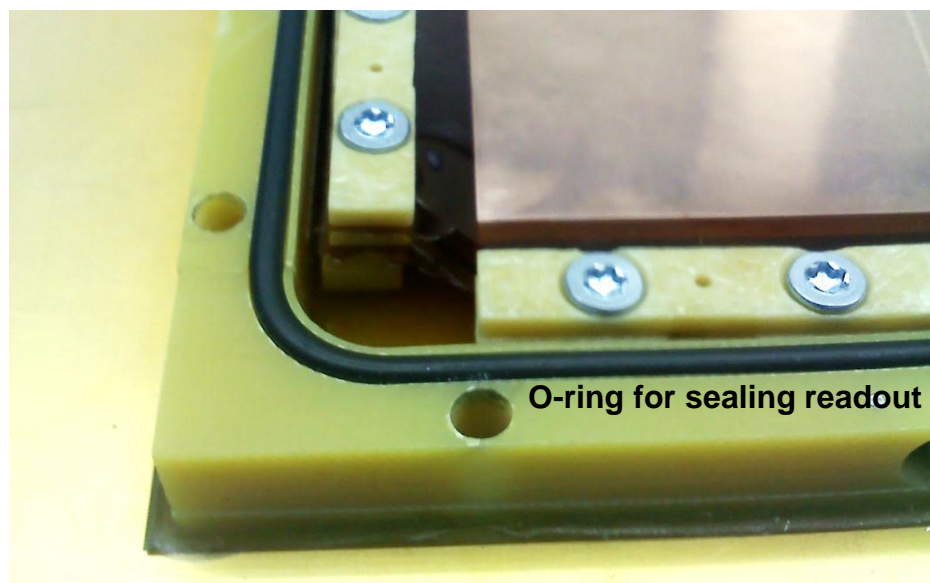
Drift with outer gas frame



Sealing outer frame with Araldite glue



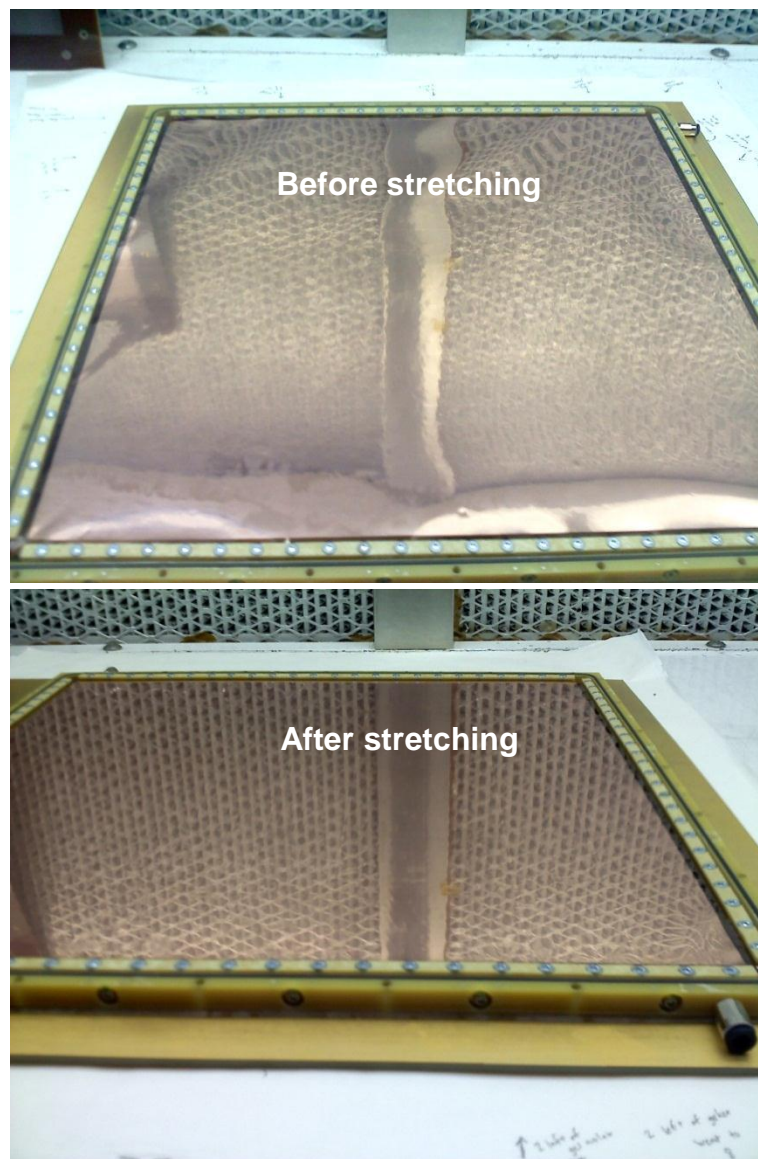
GEM foil stack with inner frame



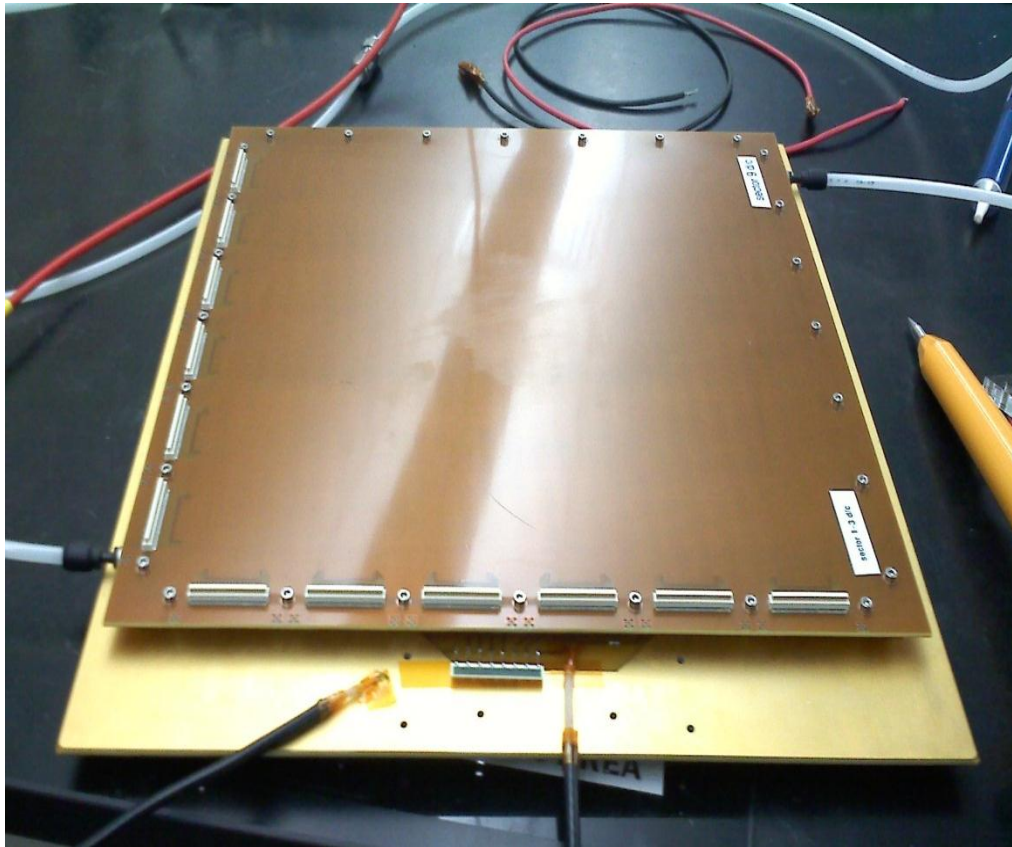
O-ring for sealing readout

# GEM foil stretching

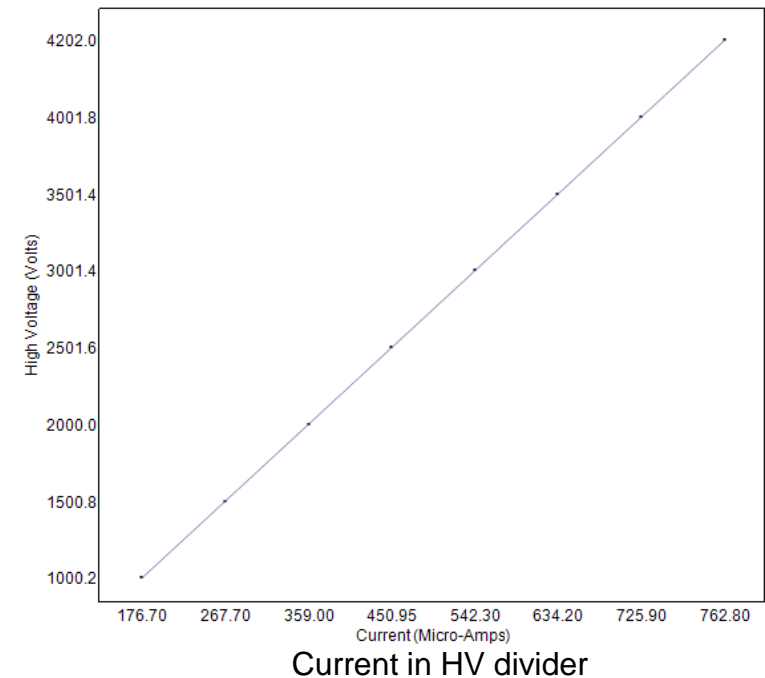
- Foil stretching is fairly straightforward and can be monitored visually
- After sufficient initial tightening we follow Rui's instructions of placing the readout board on top and continuing to stretch
- We monitor for sparks when voltage is applied between adjacent foils in air and adjust tension accordingly until no more sparks occur



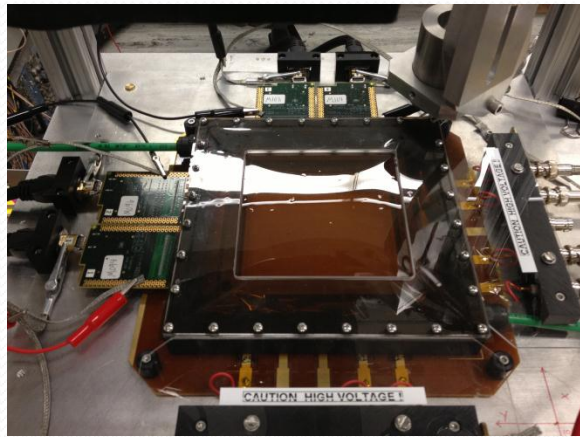




First HV test of completed GEM detector in 100% CO<sub>2</sub>

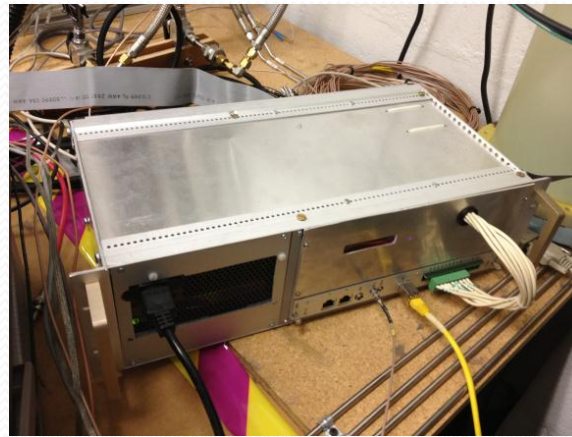


# Mini-Drift GEM Det. + SRS Readout

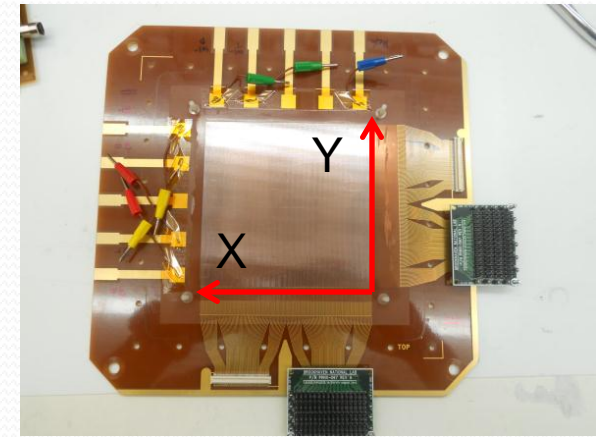


Std. 10x10cm CERN 3-GEM Det.

- ArCO<sub>2</sub> (70/30)
- Gain ~ 6500
- ~17mm Drift Gap
- Drift Time ~600ns

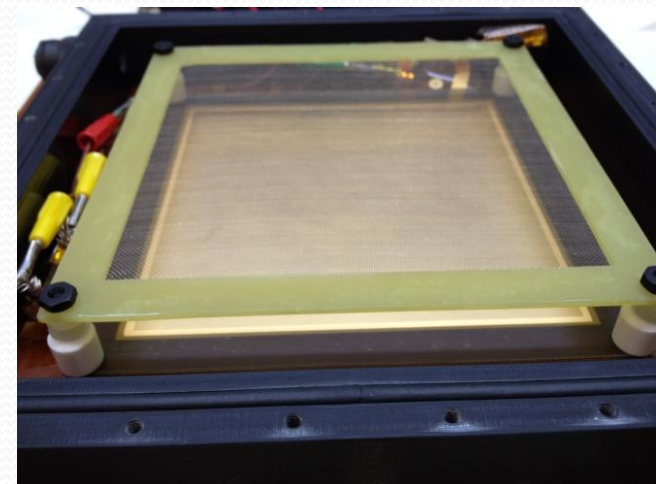
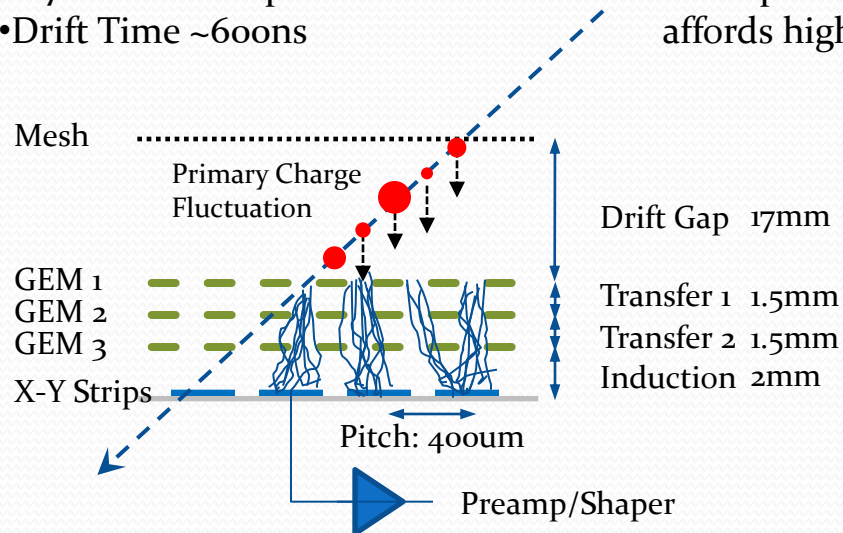


SRS /512 channels APV 25  
 • 30 x 25ns Time Samples  
 • Martin Purschke's newly developed RCDAQ affords high flexibility



COMPASS style Readout:

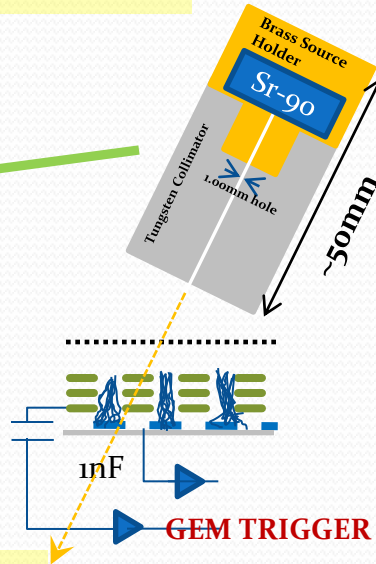
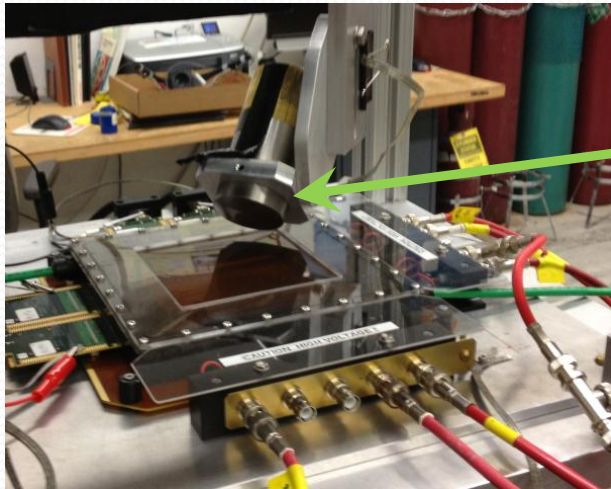
- 256 x 256 X-Y Strips
- ~10cm x 400um pitch



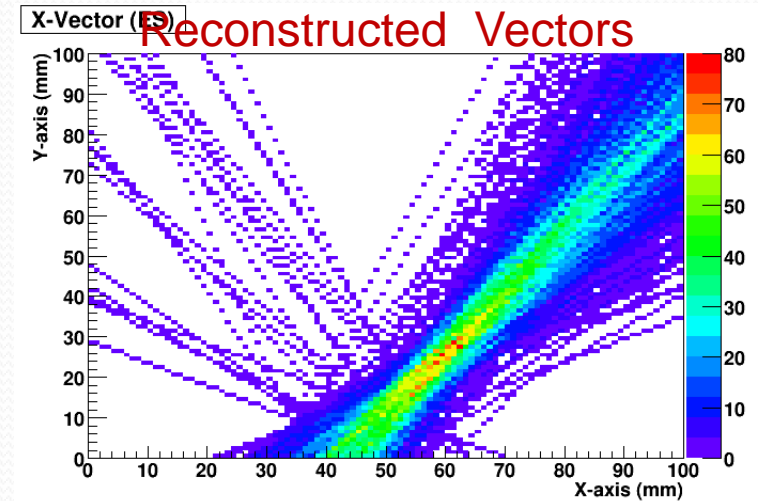


# Preliminary Bench-Top Measurements

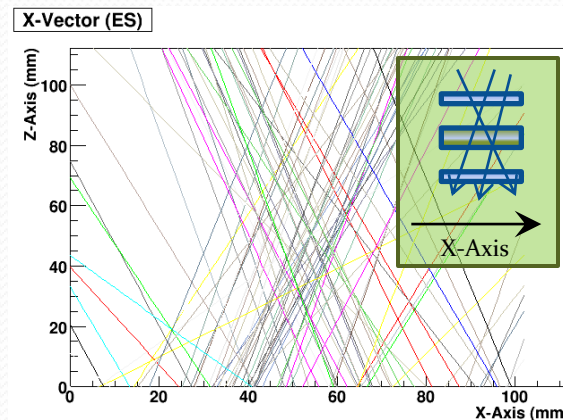
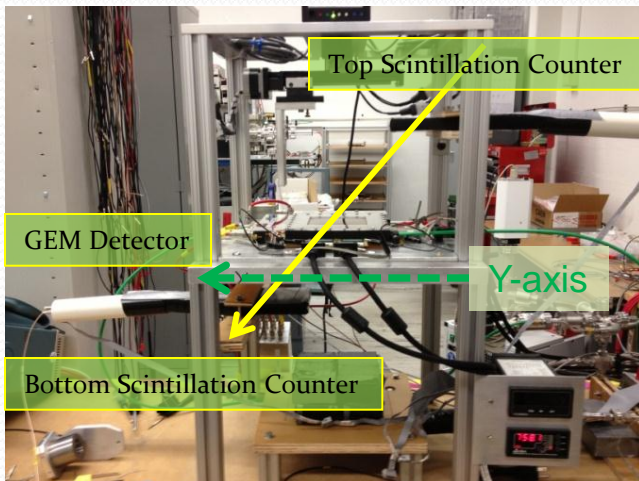
## Reconstructing Low Energy Sr90 $\beta^-$ Tracks



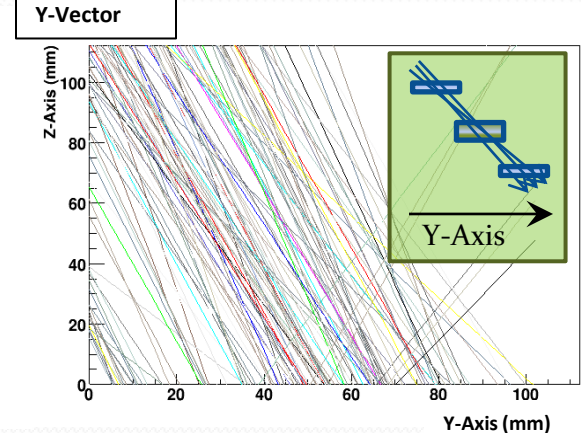
- GEM trigger doesn't provide precise timing, so rely on ability to measure the first pad fired as a measure of  $t_{\text{zero}}$
- Det. requirements: high gain, low noise, low diffusion gas
- Use timing from ADC to reconstruct z-coord. of track



## Reconstructing Cosmic Ray Tracks



## Reconstructed Vectors

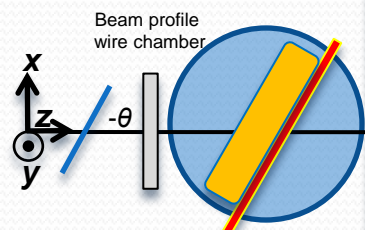


# Measuring Tracks at CERN Beam Test

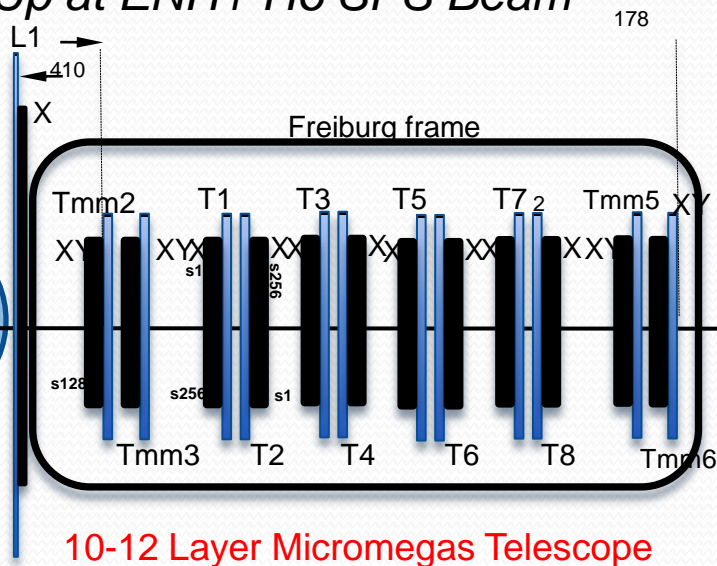
Test Beam Set Up at ENH1-H6 SPS Beam

TOP VIEW

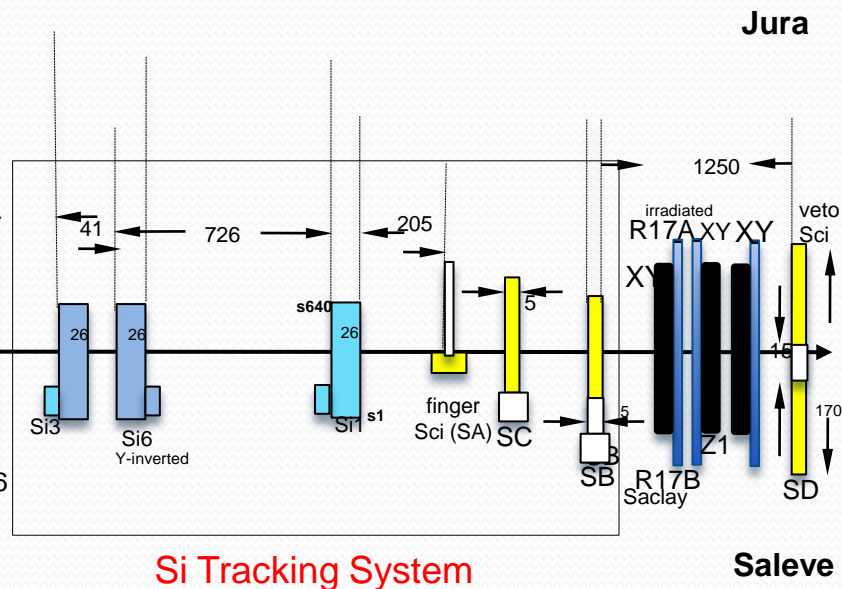
( $\pi^+$ , +120GeV/c)



**3-GEM  
Mini-Drift on  
Rotating Table**

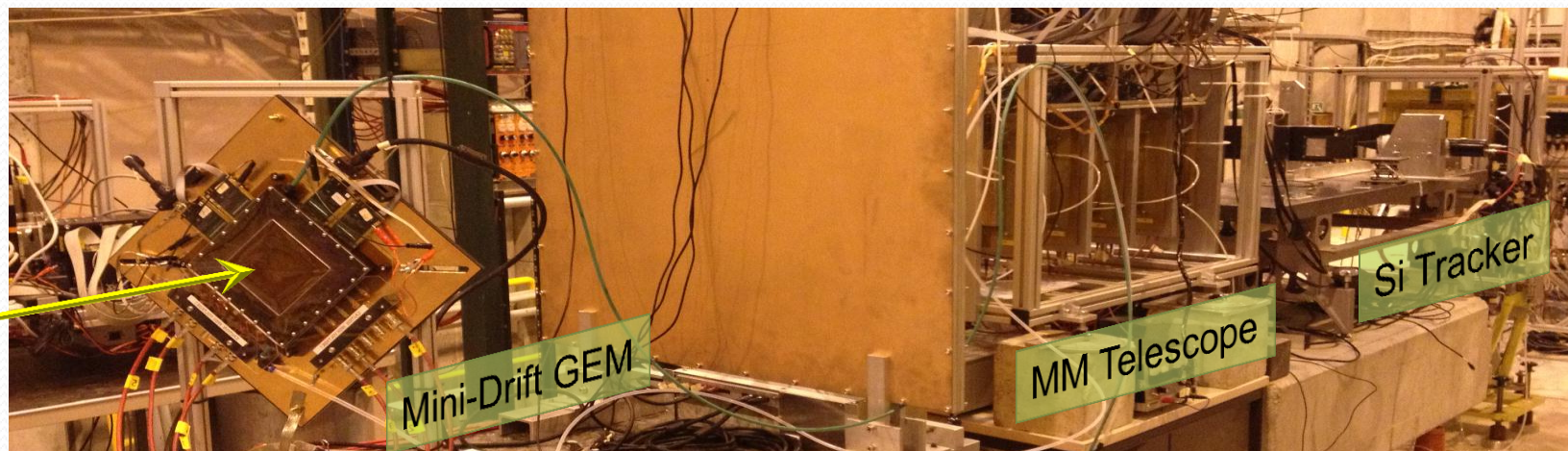


**10-12 Layer Micromegas Telescope**



**Si Tracking System**

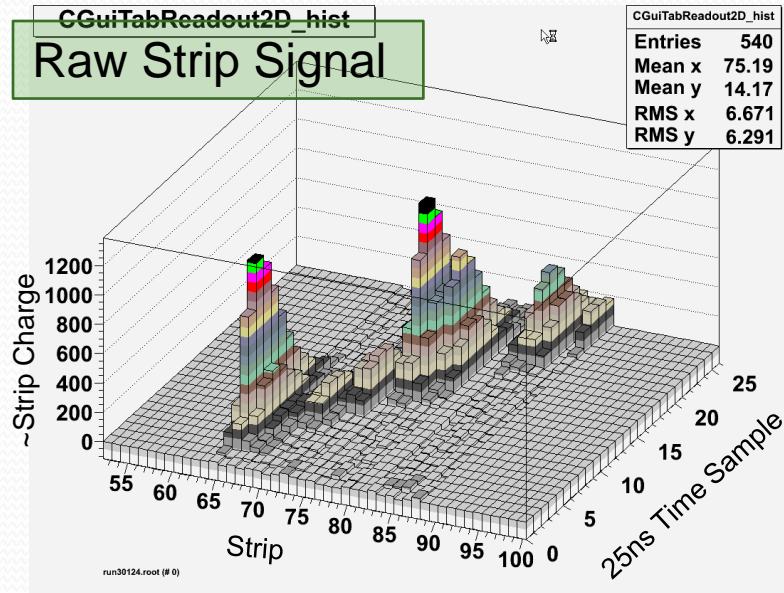
**Saleve**





# Beam Test Results (40 deg. Tracks)

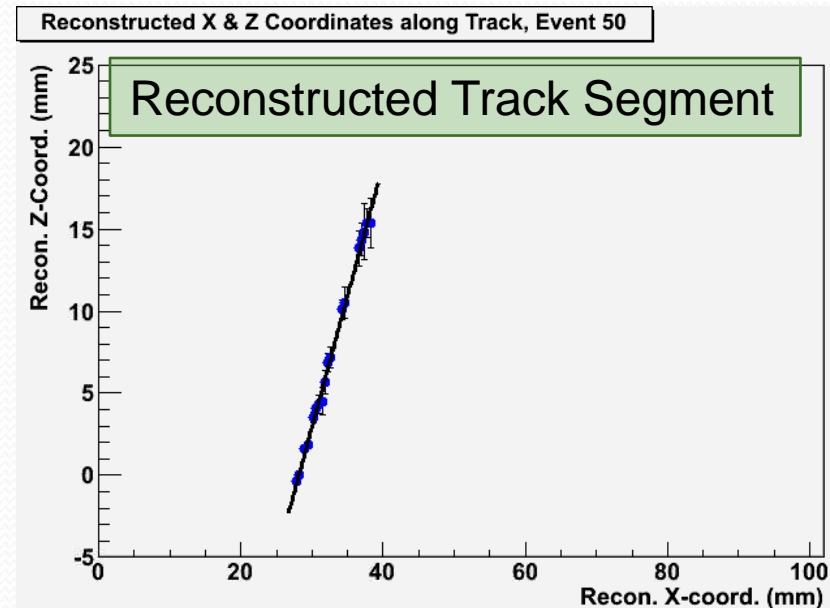
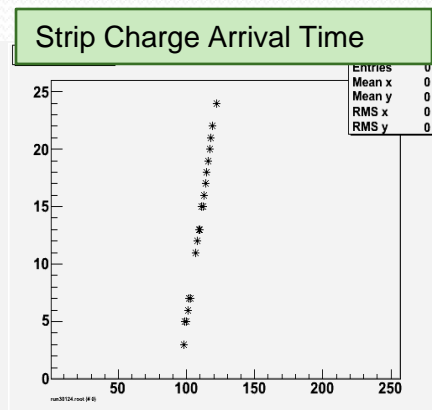
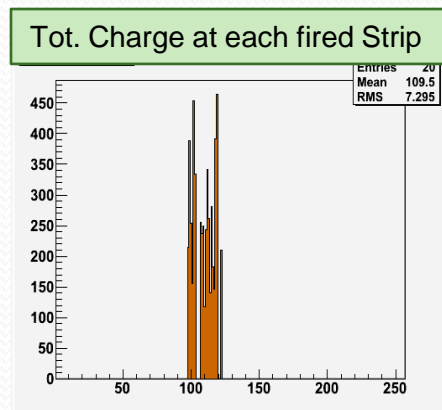
## Reconstructed Track from 1 Event



❑ The charge arrival time for each strip is determined by the time profile of the raw signal. The z-coord. is then reconstructed by taking the product of the arrival time and the drift velocity of the detector gas.

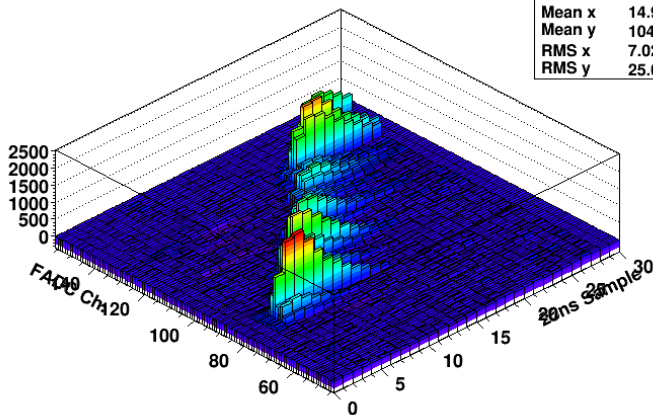
❑ The x\_coord. is taken as the center of each strip.

❑ The vector is determined from a linear fit to the reconstructed (x, y) pairs for the event.



# Data Processing

X\_Waveform: All x-Strips, Run 207, Event: 9041

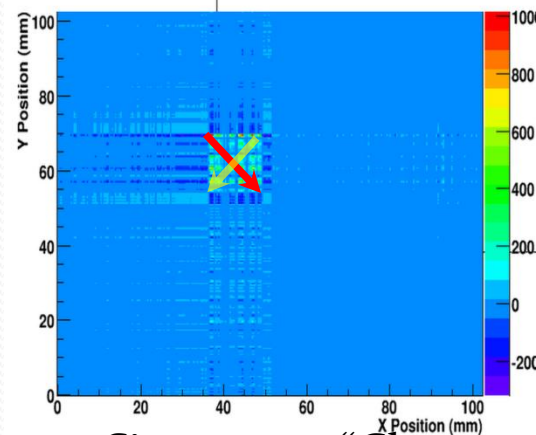


x\_waveform\_3d

Entries	7168
Mean x	14.94
Mean y	104.9
RMS x	7.026
RMS y	25.64

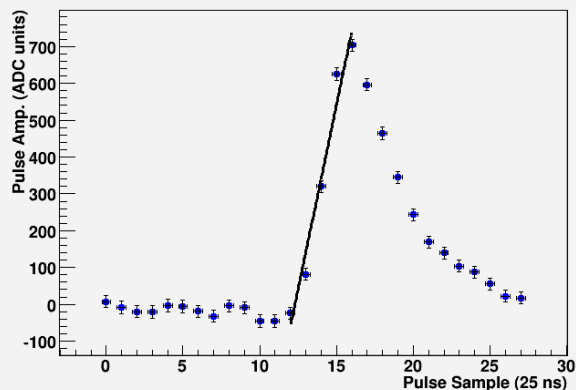
Raw Data: Waveforms in Time

XY Pad Correlation (RAW), Run 207, Event 9042



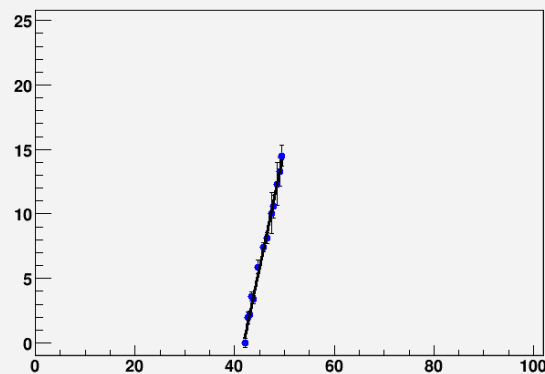
Vector Signature: “Charge square”

X-Pulse Rising Edge Fit\_114, Run 207, Event: 37



- Linear Fit to determine arrival time = x-int.
- 30 samples x 25ns = 750ns window

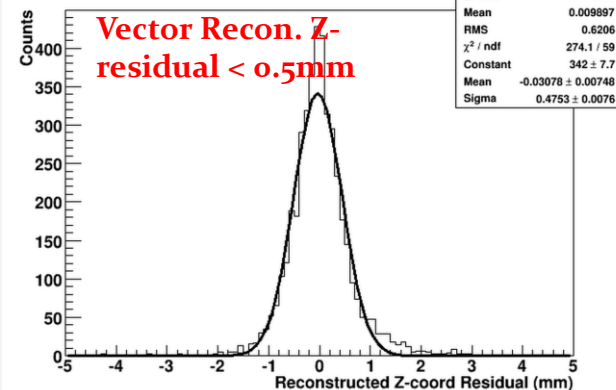
Reconstructed X & Z Coordinates along Track (Ver.2), Run 207, Event: 28



## Vector Recon:

- X -coord. = middle of pad
- Y -coord. = drift time \* Drift Vel.
- Fit (x,z) points to line

Distr. of Y-Vector Residuals point-by-point, for all Events, Run207



x_vector_residuals_es	
Entries	4358
Mean	0.009897
RMS	0.6206
$\chi^2 / \text{ndf}$	274.1 / 59
Constant	342 $\pm$ 7.7
Mean	-0.03078 $\pm$ 0.00748
Sigma	0.4753 $\pm$ 0.0076

## Propagated Errors:

Angle:  $\sim \pm 18 \text{ mrad}$

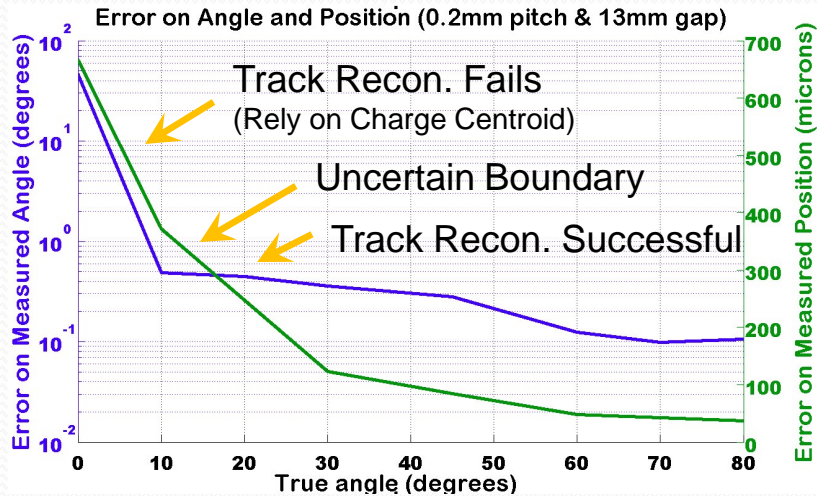
Charge arrival time:  $\sim \pm 1.8 \text{ ns}$



# Angular and position Resolution

## A first look at the Angular and Position Resolution

### MC Simulation of Angle and Position Resolution

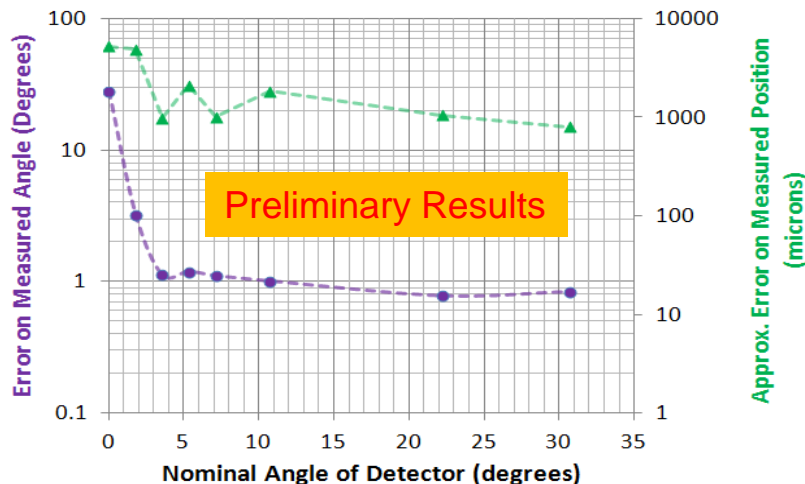


❑ As a first attempt to determine the angular and position resolution, we do so without the aid of a reference track, determined by the high precision reference detectors within the beam test set up.

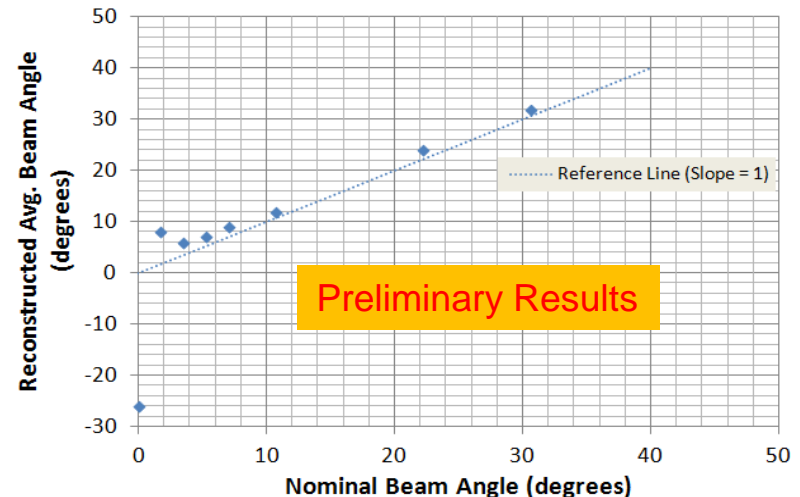
❑ The angular resolution is determined here by simply taking the spread in the distribution of the reconstructed vector angle. This is known to be a reasonable approximation since the beam divergence is minimal.

❑ The position resolution is determined by unfolding (in quadrature) the spread in the charge centroid distribution at zero degrees from the reconstructed position of the vector at the window of the detector, which is generally a poor approximation.

### Measured Position and Angular Resolution

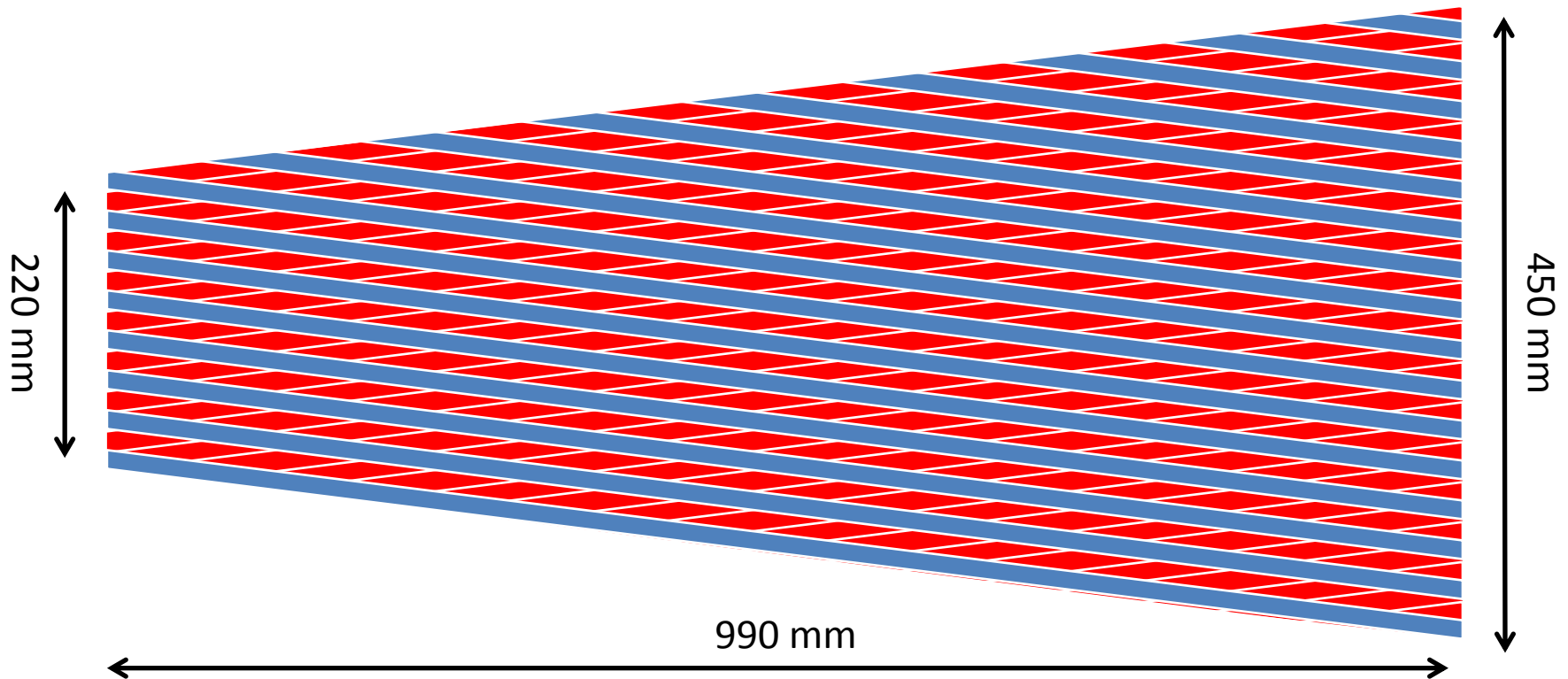


### Nominal Beam Angle Vs Measured Angle

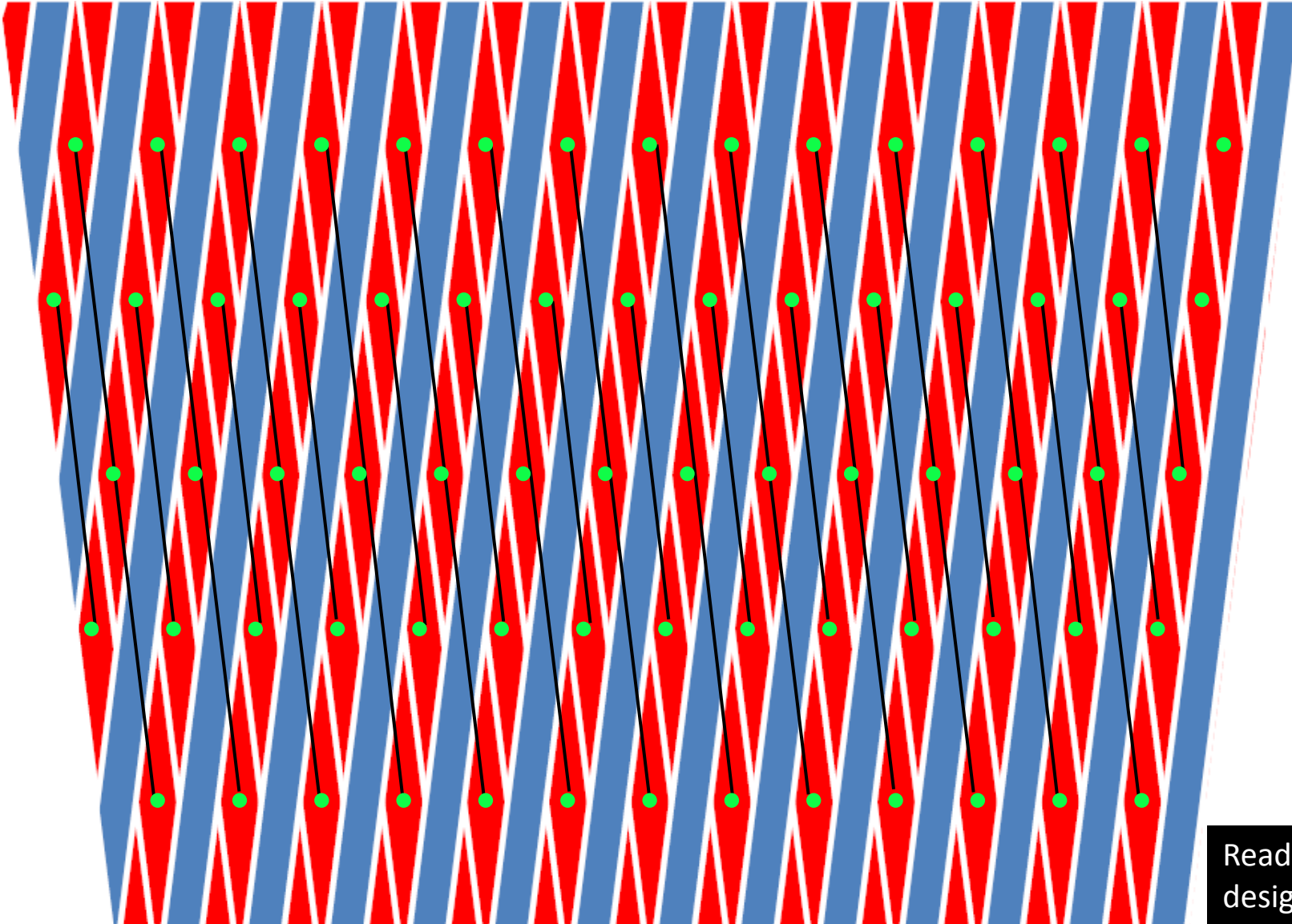


# 2D stereo angle Readout for UVa EIC Large GEM chamber

- Suggested readout scheme:
  - a 2D readout optimized to get high accuracy in the  $\phi$  coordinate, lower but sufficient resolution in the  $r$  coordinate.
  - each set of stripes parallel to one of the radial sides of the module: strip pitch is 0.6 mm.
  - Issues: **High capacitance in long readout strips; will signal-to-noise be an issue ?**



# 2D stereo angle Readout for UVa EIC Large GEM chamber



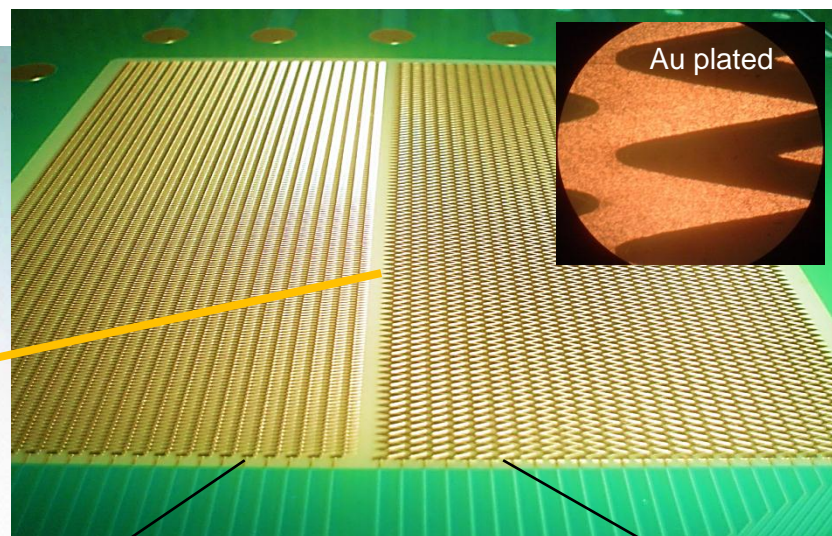
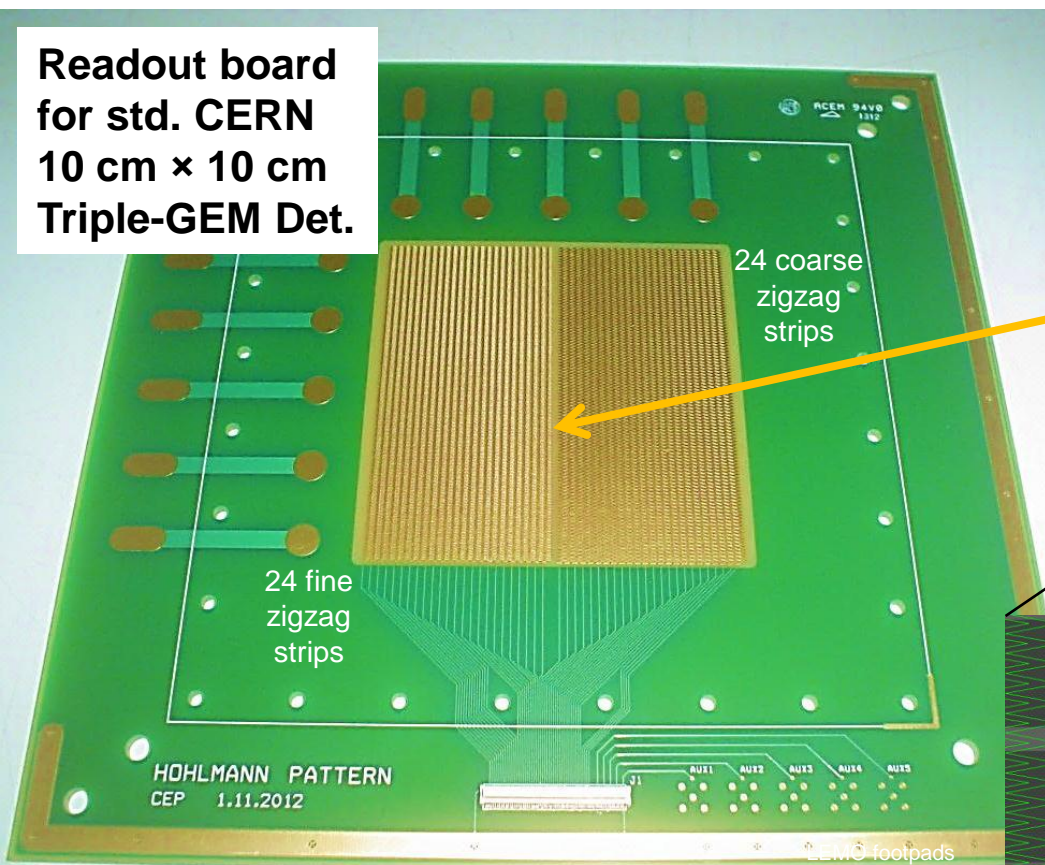
Readout plane  
design is currently  
underway



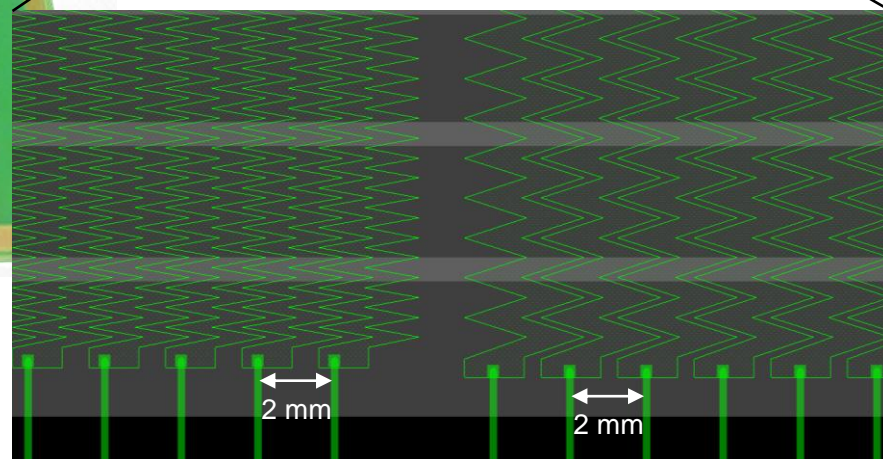
# Zigzag strip readout board



Readout board  
for std. CERN  
10 cm × 10 cm  
Triple-GEM Det.



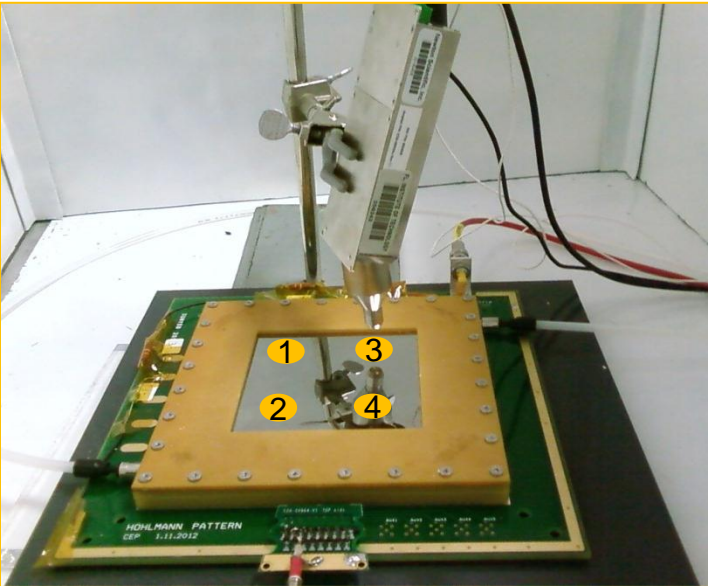
2 sets of 10cm zigzag strips with  
different zigzag pitch (along strip)



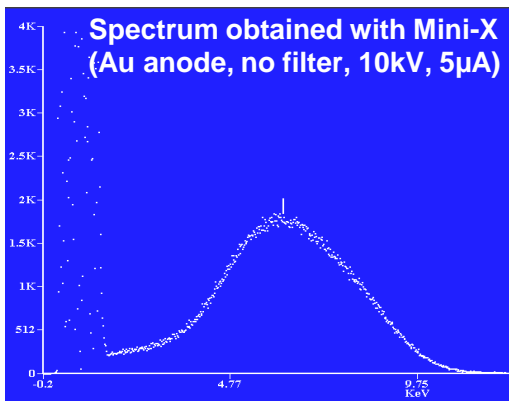
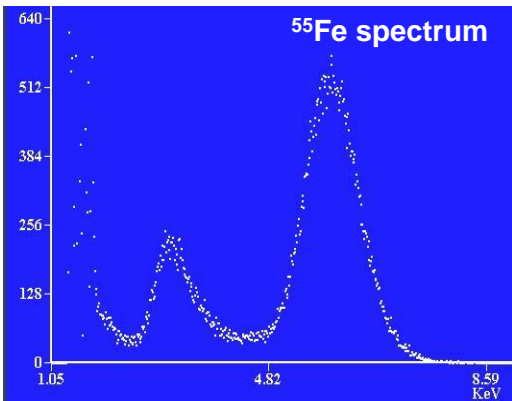
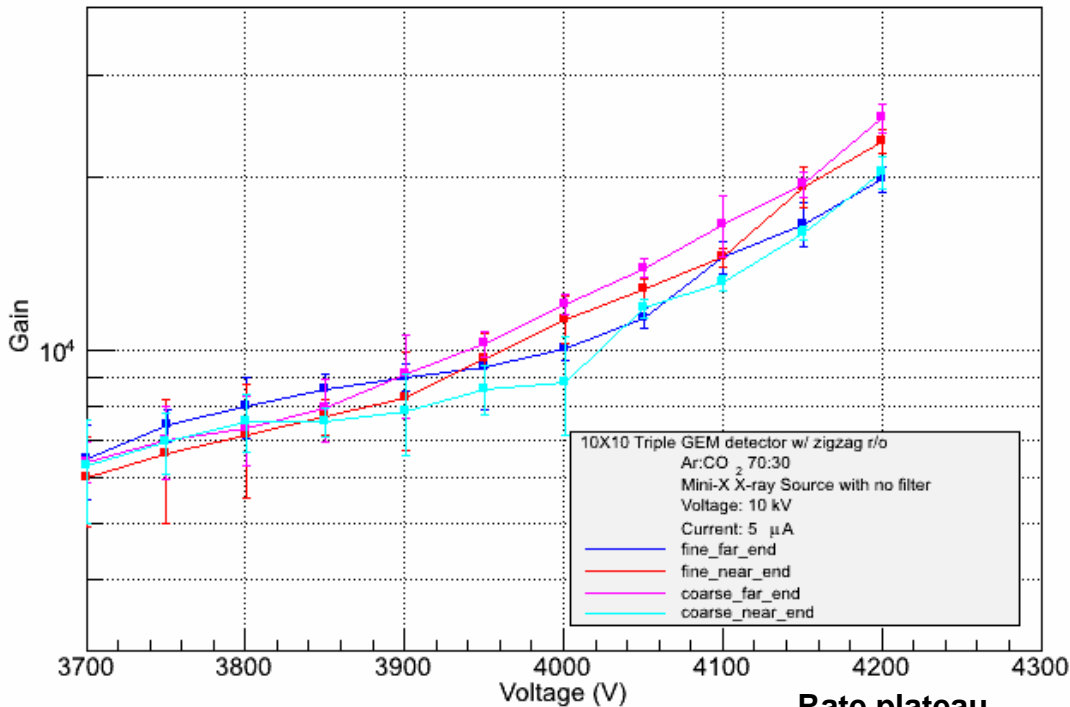
CAD Design by C. Pancake, Stony Brook

# E<sub>IC</sub> Zigzag-GEM bench tests

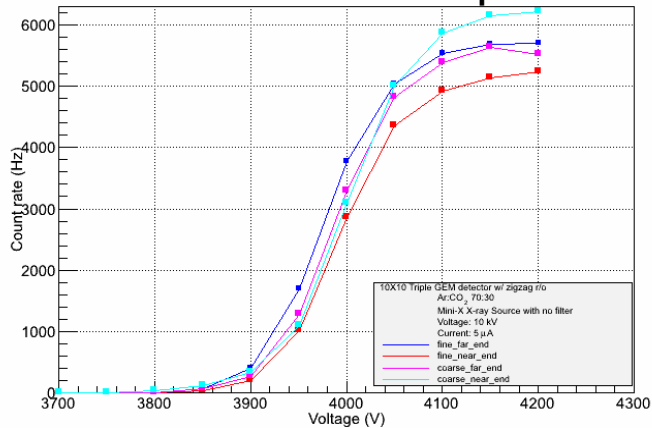
“Mini-X” x-ray source inside 3' × 2' × 2' lead-shielded box  
(procured / constructed with funds from this project)  
irradiating 10cm × 10cm Triple-GEM with zigzag readout



## Gas gain measurements at four spots



## Rate plateau





# E<sub>I</sub>C 2012 RD51 beam test @ SPS



**RD51 GEM Tracker**  
 Contact Persons:  
 Leszek Ropelewski  
 [Leszek.Ropelewski@cern.ch]  
 Yorgos Tsipolitis  
 [yorgos.tsipolitis@cern.ch]

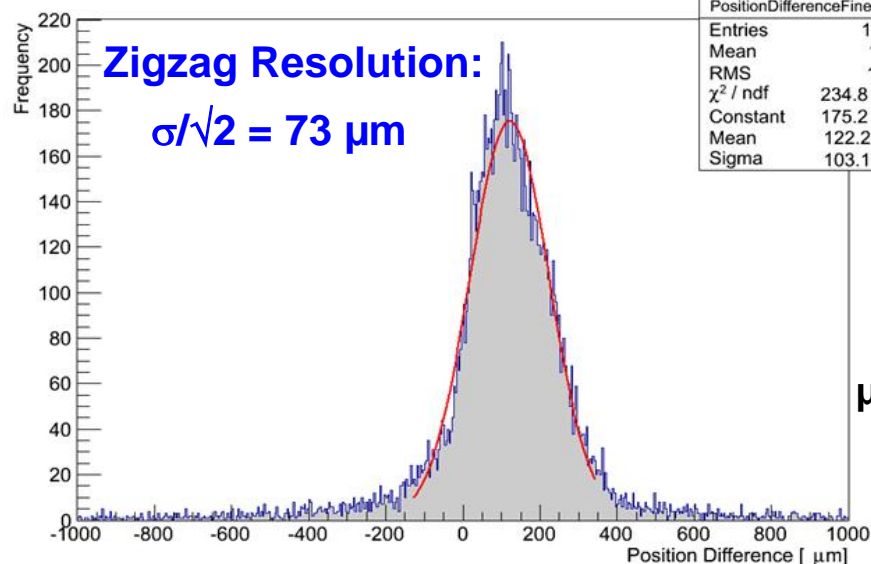
2 zigzag detectors mounted in a stack



SRS  
r/o



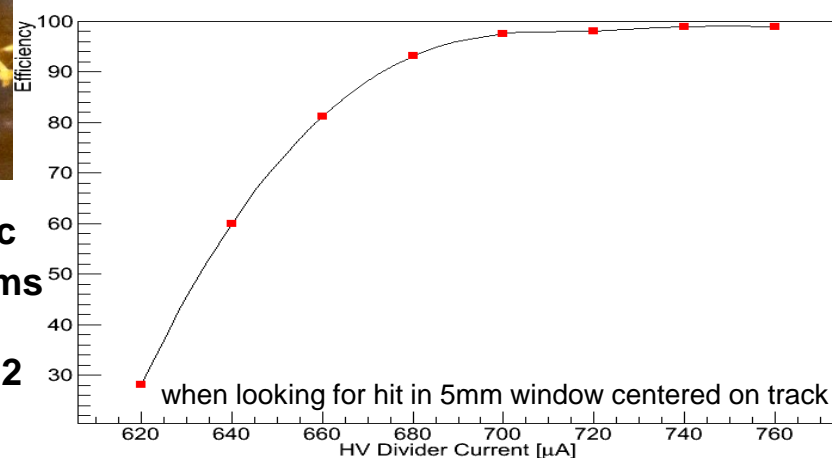
Position Difference Fine Strips



150 GeV/c  
 $\mu$  &  $\pi$  beams

June 2012

Efficiency Vs. Divider Current for ZigZag GEM





- **Setting up gain uniformity measurements using Mini-X x-ray and Scalable Readout System (SRS)**
  - noise is low for zz strip r/o (few ADC counts pedestal width)
  - triggering on signal from bottom of GEM 3 established
- **Designing larger pcb with zigzag readout strips for “S4” 30cm × 30cm Triple-GEM**
  - Strip pitch =  $30\text{cm}/128 = 2.3\text{ mm}$  to read out entire 30cm width of GEM detector with a single APV25 hybrid (128 ch.)
  - Planned zigzag strip length: 10 cm
  - Additional sections with radial zigzag strips on same pcb to test for use in a larger trapezoidal GEM
  - Currently slow going due to inexperience with pcb design work (undergraduate); expect major boost from post-doc hire

- Transfer know-how with S4 GEM to EIC forward tracking colleagues from U. Virginia: Kondo Gnanvo to visit Fl. Tech Dec 18-21 for a training session on S4 construction
- Test S4 GEM response uniformity w/ x-ray source & SRS
- Finish design of zigzag r/o board for S4 GEM and get a few boards manufactured
- Develop a simulation of zigzag strip readout in ANSYS and GARFIELD
- Test zigzag GEMs in magnetic field (bench top, test beam?) to check impact on spatial resolution
- Construct a  $\sim 1\text{m} \times 0.4\text{m}$  trapezoidal S4 GEM
- Design and test zigzag pcb for the  $1\text{m} \times 0.4\text{m}$  trapezoidal S4 GEM

## 3-coordinate GEM readout

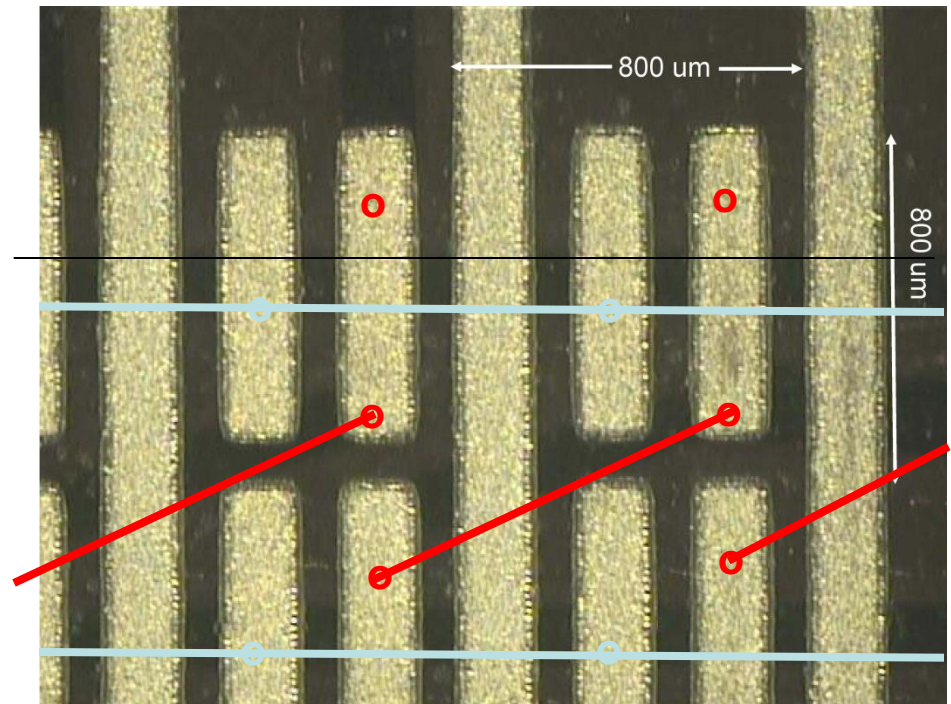
For a given track density, 3-coordinates from one chamber will allow larger chamber sizes which will **reduce readout costs and material**.

Extension of the 2-coordinate strip/pad readout. Add another set of pads connected diagonally (red, vias and traces on back).

We have 800  $\mu\text{m}$  pitch boards, chamber parts in hand

RD51 SRS readout system ordered last February is finally available at CERN so we hope to begin all the “usual” tests early next year.

Proposing a run in the SLAC test beam next spring

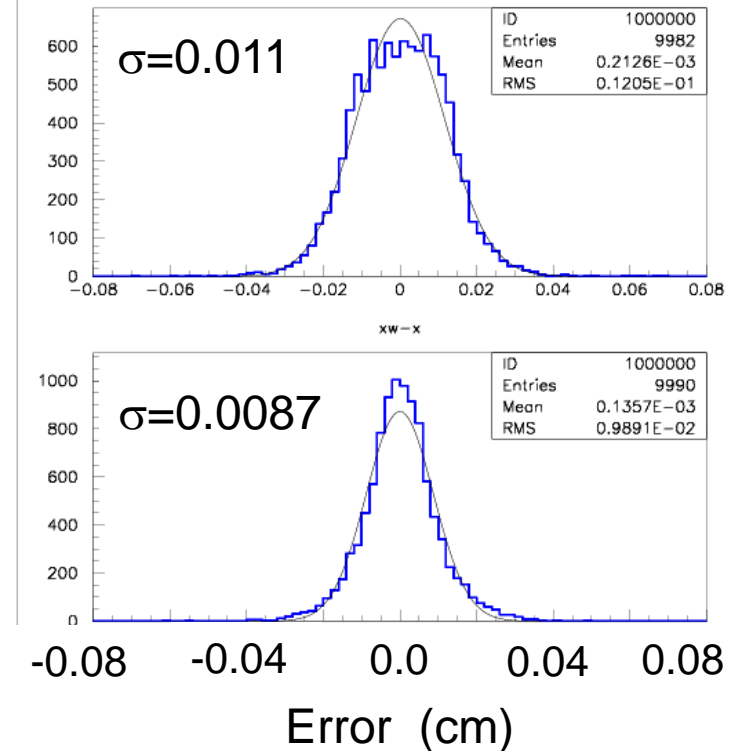
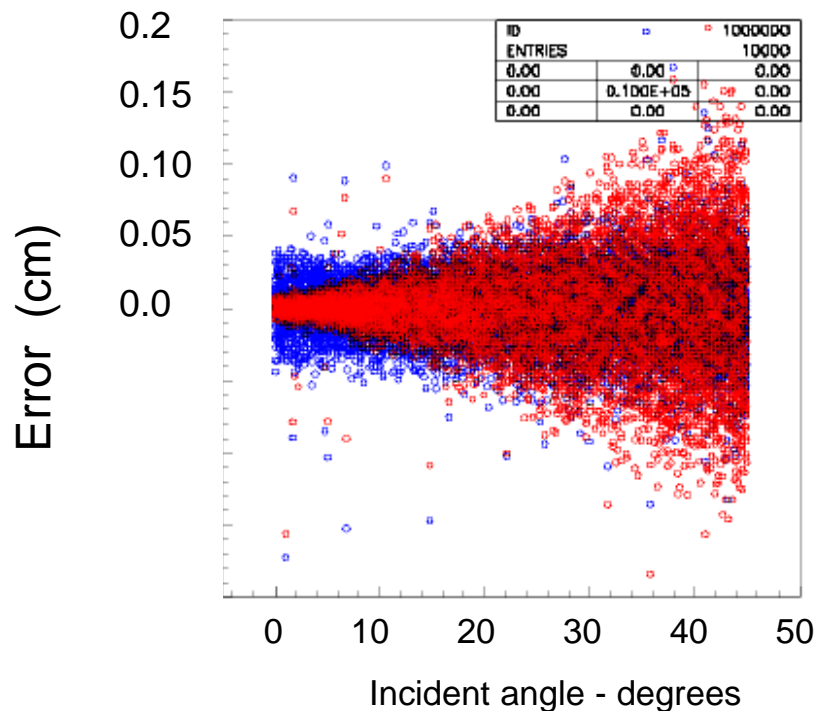




# GEM detector simulations

We have developed a detailed simulation for GEM structures over the past year and have been testing it against 2-coordinate chambers

It is already showing interesting results for analysis algorithms.

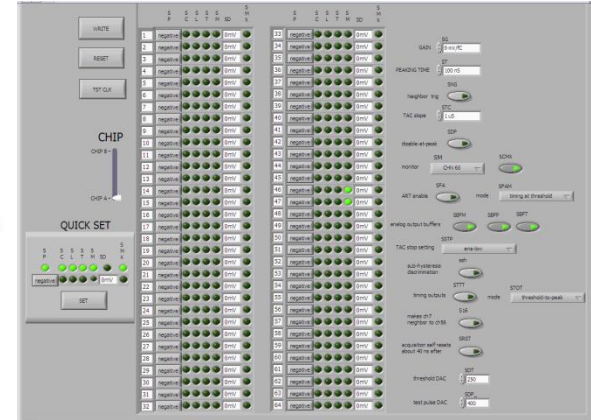
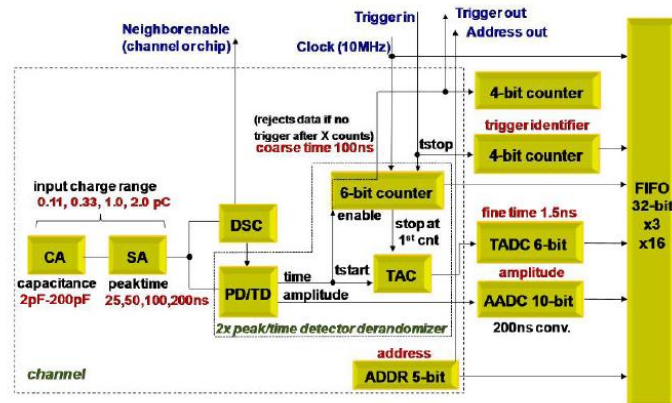


Resolution for 800 um pitch and 600 um pitch chambers from simulation

Resolution vs. incident angle using  
charge weighted average of hit strips  
and average position of hit strips

## **Plans for the coming year**

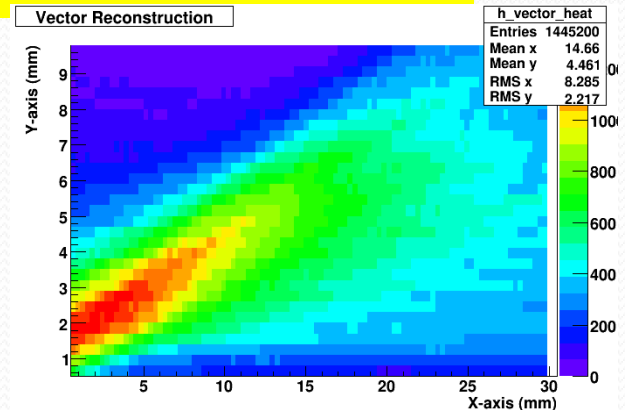
- Commission SRS readout system – early 2013
- Test 3-coordinate chambers with  $^{55}\text{Fe}$  source and cosmic rays. Measure basic parameters (gain, cross talk, charge sharing, upper limit on resolution, lower limit on efficiency) Winter/Spring 2013
- Run chambers in test beam (measure resolution, resolution vs. incident angle, ...) Spring/summer 2013



## VMM<sub>1</sub> Labview Control panel

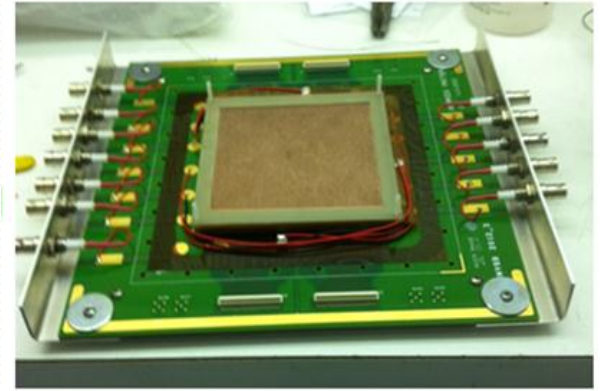
- ## Preliminary Results (64 ch.):

- 
- Charge Sum**
- Counts
- Primary Charge (Ne-)
- |                |
|----------------|
| h charge sum   |
| Entries 150033 |
| Mean 198.1     |
| RMS 55.69      |

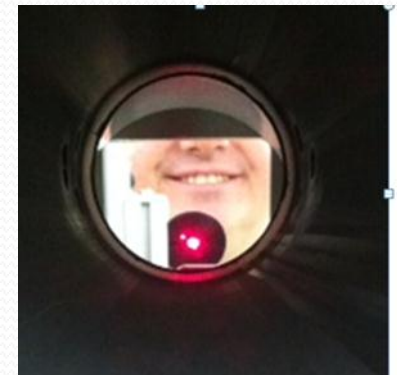




# Forward CsI RICH Progress.

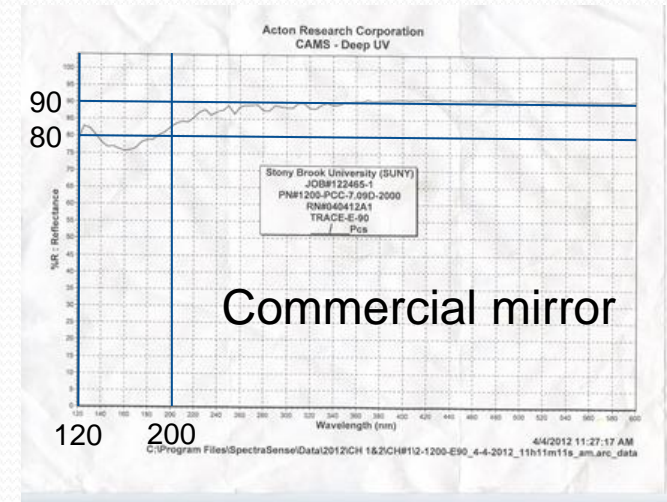


- J-Lab tests disappointing:
  - 2 million events w/ 15 tracks...none electrons.
- Test be requested at SLAC March 2012:
  - New GEM foils...multiple strips like PHENIX.
  - Second pad plane...hexagons to see rings.
  - New trip detection system:
    - Capacitive coupling off resistor chain.
    - Integrated with PHENIX HBD HV relays.



# Mirror Developments

- Cherenkov photon yield primarily at small  $\lambda$ .
- Deep UV mirrors use 250 Å MgF<sub>2</sub> overcoat to act as dielectric mirror.
- Plans:
  - Year 1: Develop in-house manufacture of small mirrors.
  - Year 2: Scale up to use Big Mac
- First in-house mirror made!
- Reflectivity tests pending at BNL.



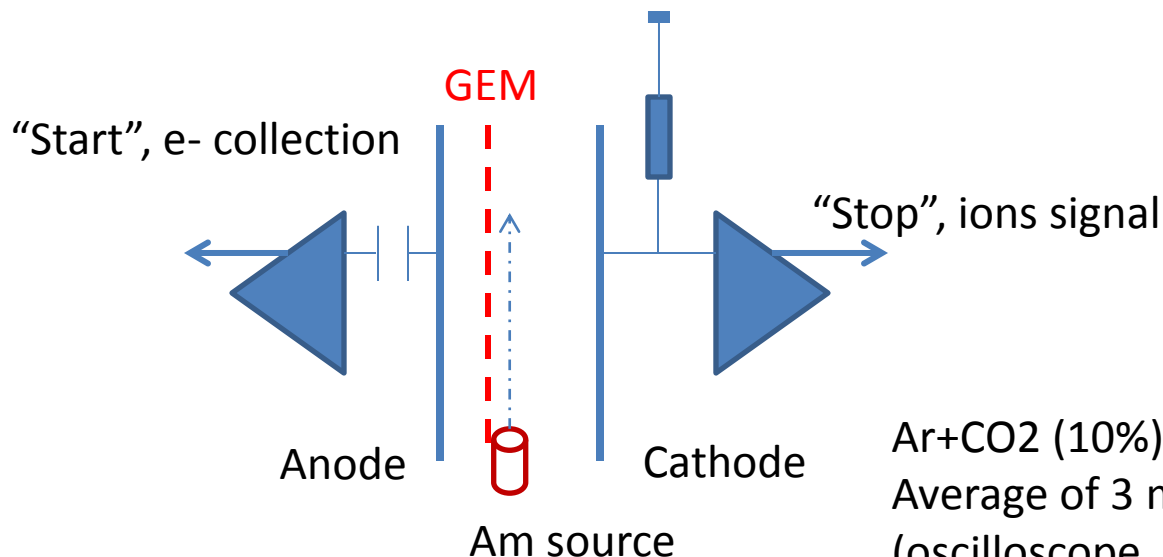
# Summary

- Despite funding division across fiscal boundary, we have significant progress on all fronts:
  - Postdoc long/strong list of candidates.
  - TPC/RICH
  - Forward Tracking
  - Forward HBD
- Multiple options in parallel development.
- Expect continued progress in the coming year.



# Backups

- Setup to measure mobility of positive ions
- Single GEM foil is working as gas amplification for  $\alpha$ -particle ( $\text{Am}^{241}$ ) primary ionization



Ar+CO<sub>2</sub> (10%)

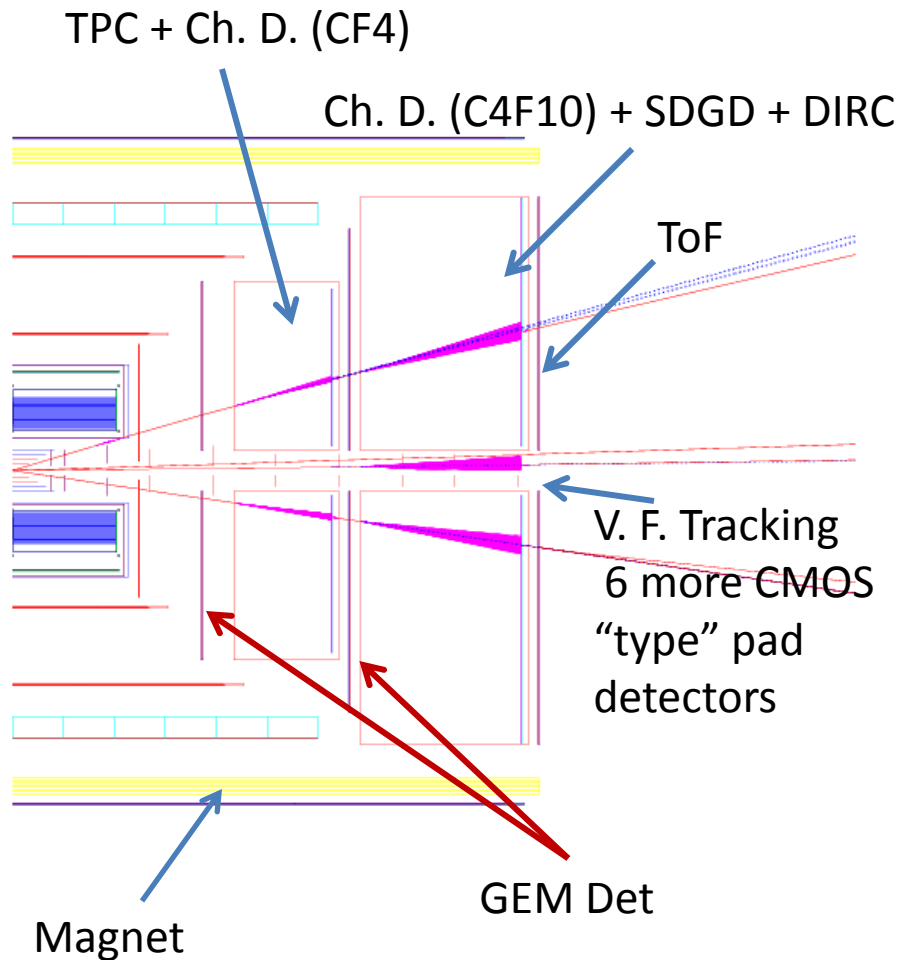
Average of 3 measurements  
(oscilloscope, no calibration)

for different E-fields in drift region :

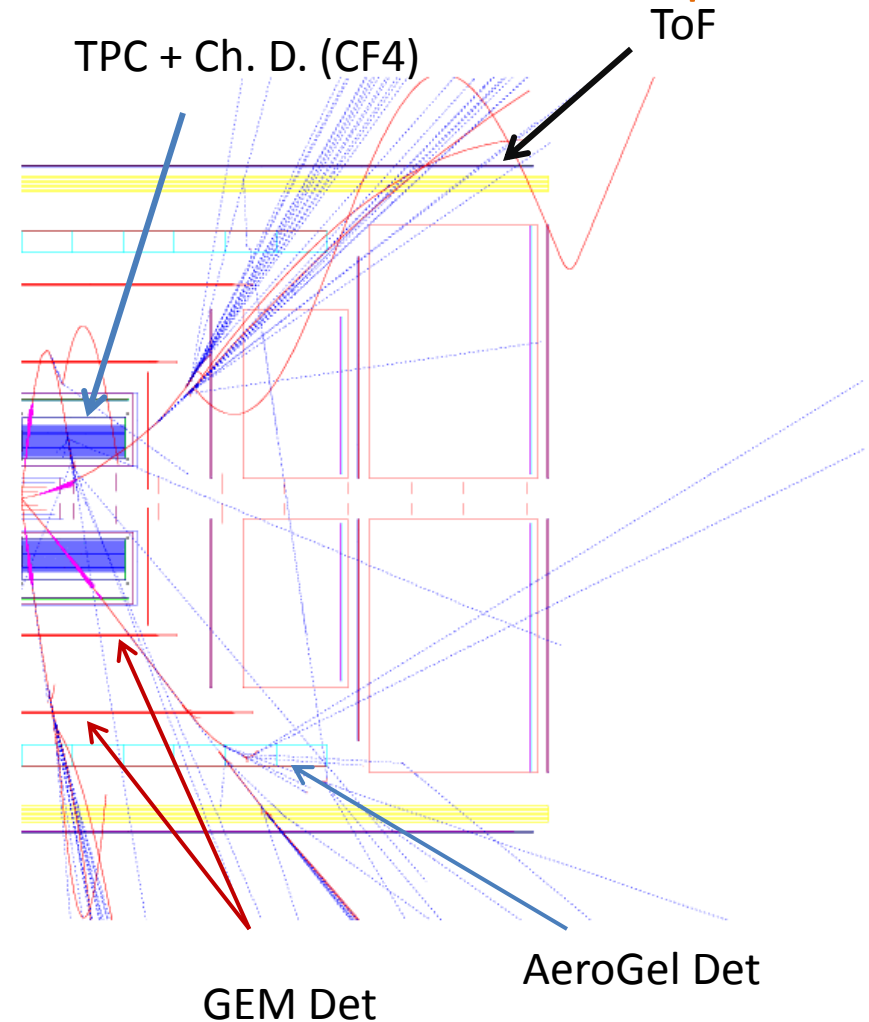
$\langle \text{Mobility} \rangle \sim 1.04 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$

Set-up in simulation; SC magnet  $B_z=2. \text{ T}$ ,  $R=1.5 \text{ m}$ ,  $dZ=2.5 \text{ m}$ ;  
(EMCALs not shown)

### “Forward” set-up

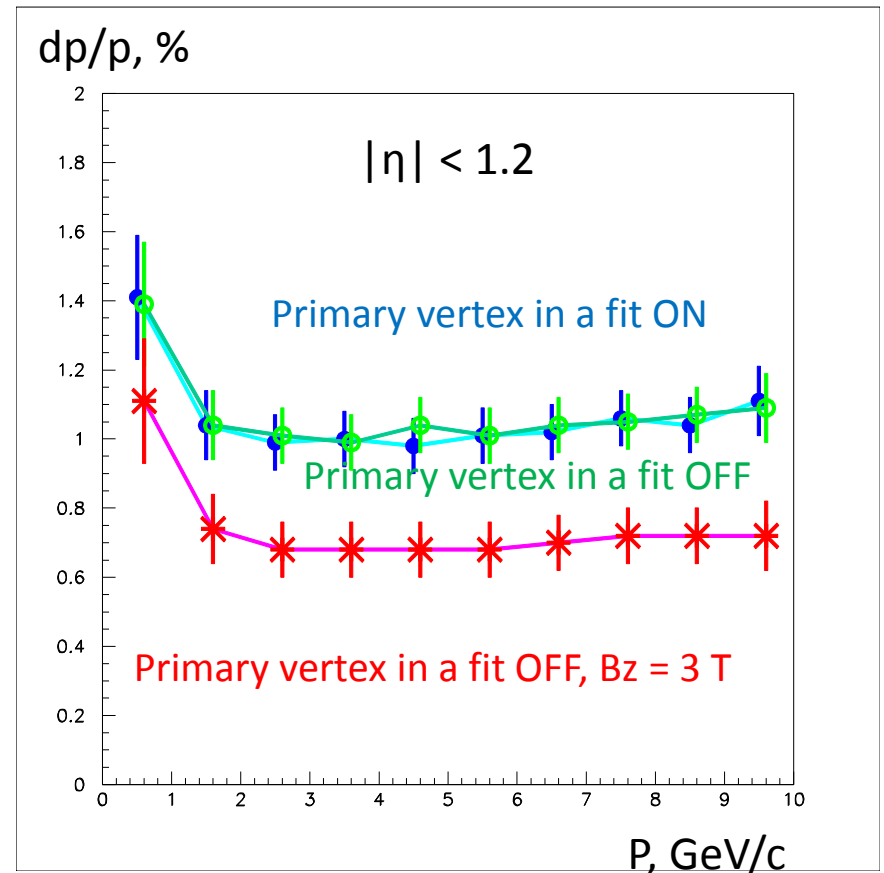
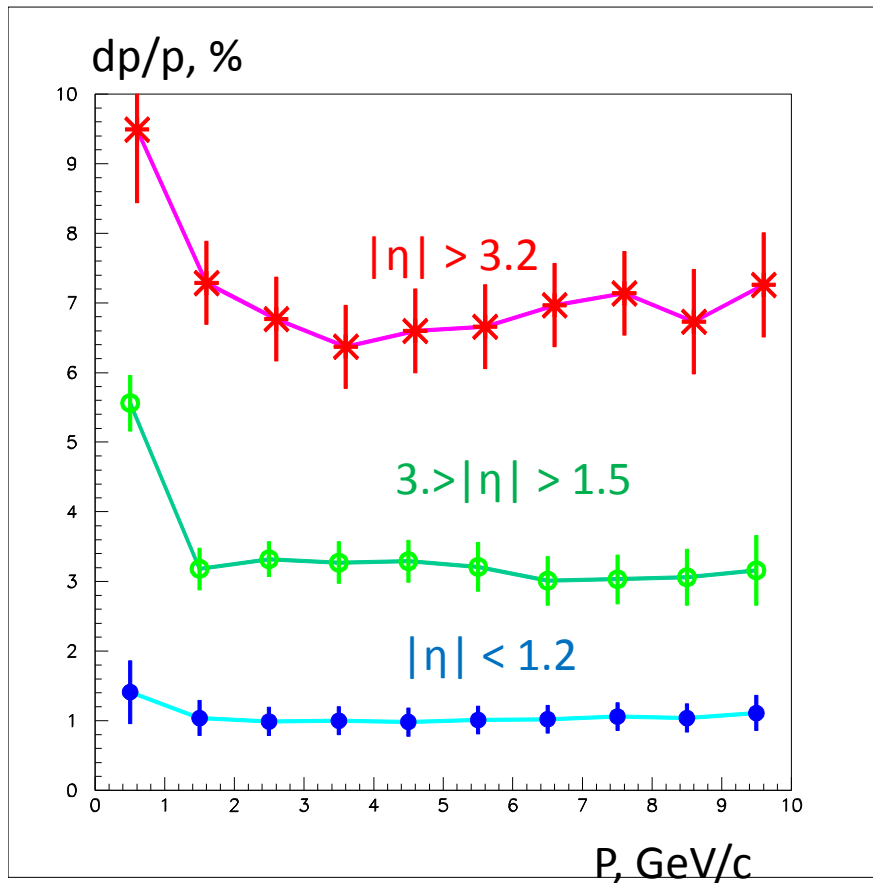


### “Barrel” set-up





# dP/P performance (%); one $\pi^-$ / event; $B_z = 2. \text{ T}$

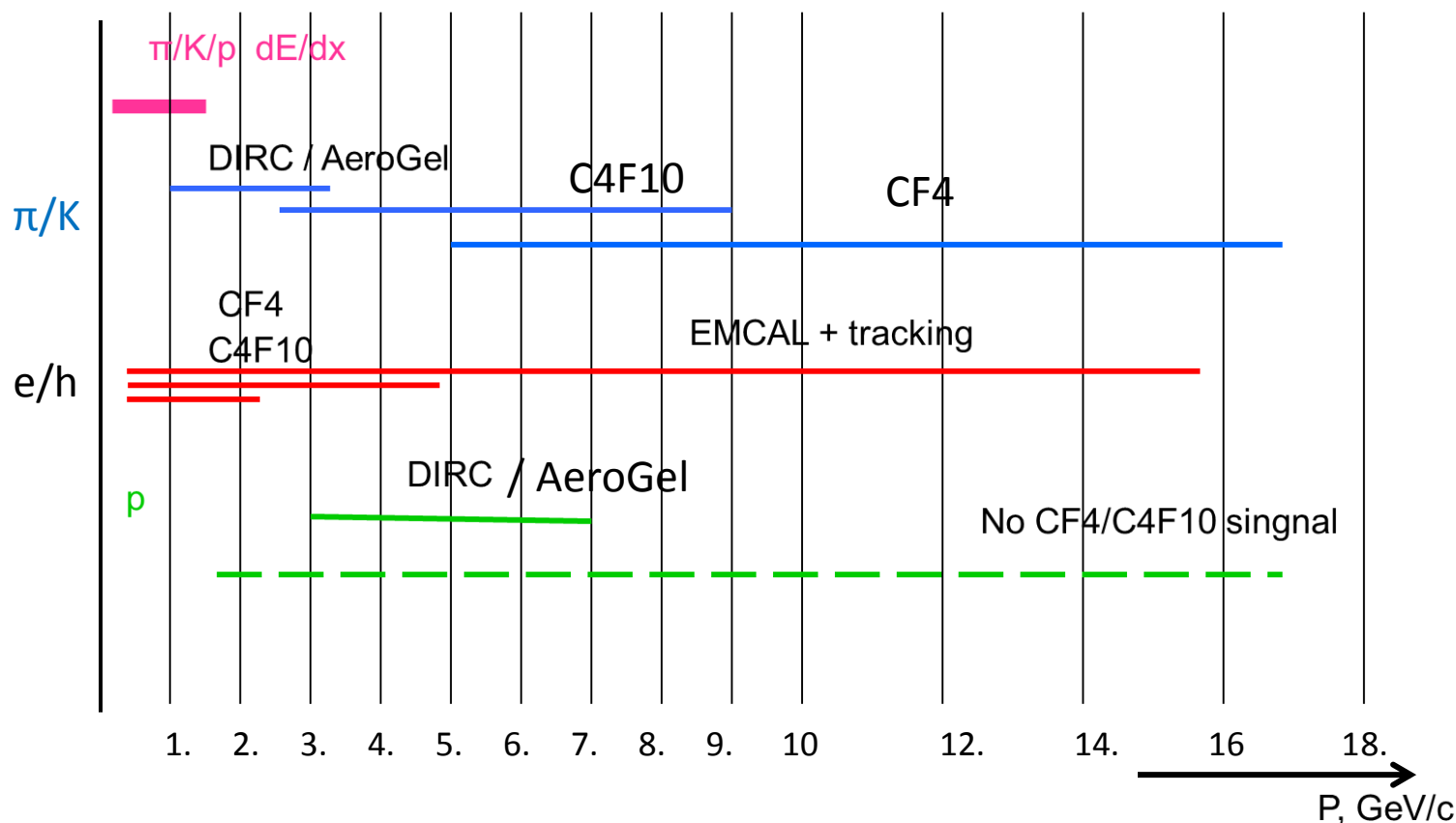


# PiD performance for particle P (GeV/c)

	dE/dX	DIRC/Aerogel	C4F10*)	CF4	EMCAL
$\pi/K$	0-1. (1.5)	1-3 (1-4)	2.5-9	5 – 17	
e/h	0-0.2	< 0.5	<2.5	< 5.	> 0.5
p	0-1.5	3-7	< 17. (no signal)	<30 (no signal)	

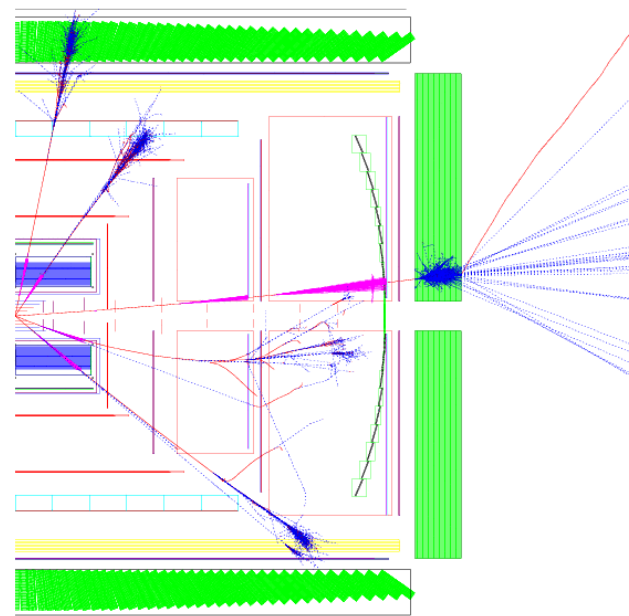
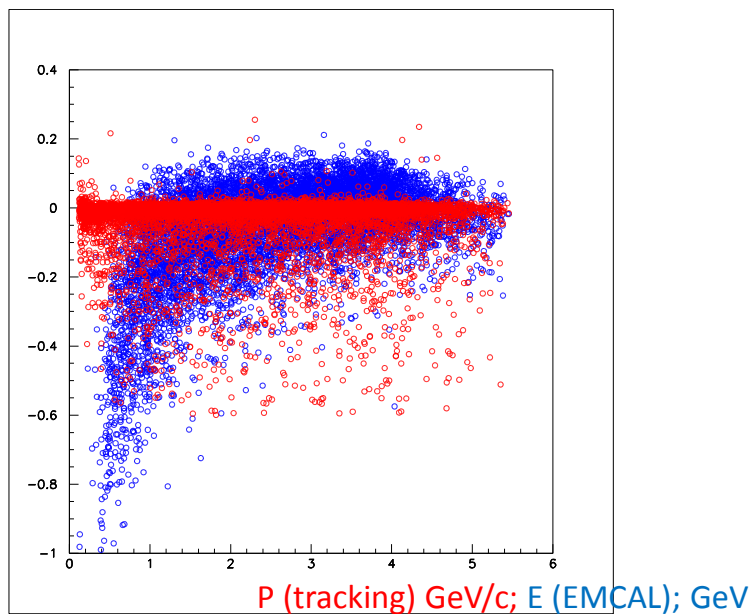
\*) Forward only

## Electron and Hadron PID

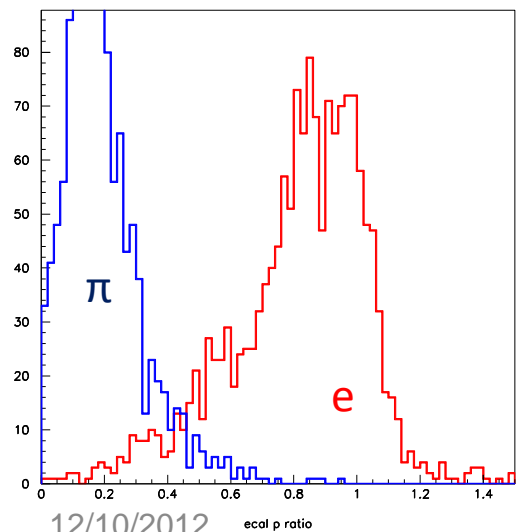


# Response to electrons ( tracking –EMCAL)

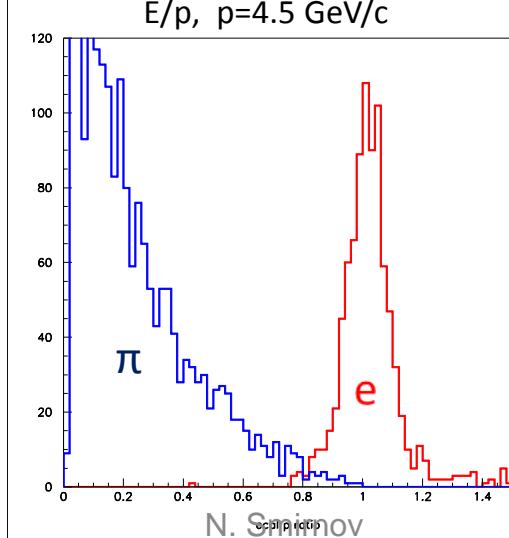
$dp/p$ ;  $dE/E$



$E/p$ ,  $p=1.5$  GeV/c



$E/p$ ,  $p=4.5$  GeV/c



12/10/2012

N. Spirnov



# Conclusion from detector setup performance simulation

- Fast, low diffusion TPC (CF<sub>4</sub> based gas mixture) both in barrel and Forward in a “combination” with Cherenkov Detector
- And “Short Drift GEM Detector” as a possible “Three – in – one” set-up in Forward
- Are crucial elements of this eRHIC Detector setup option

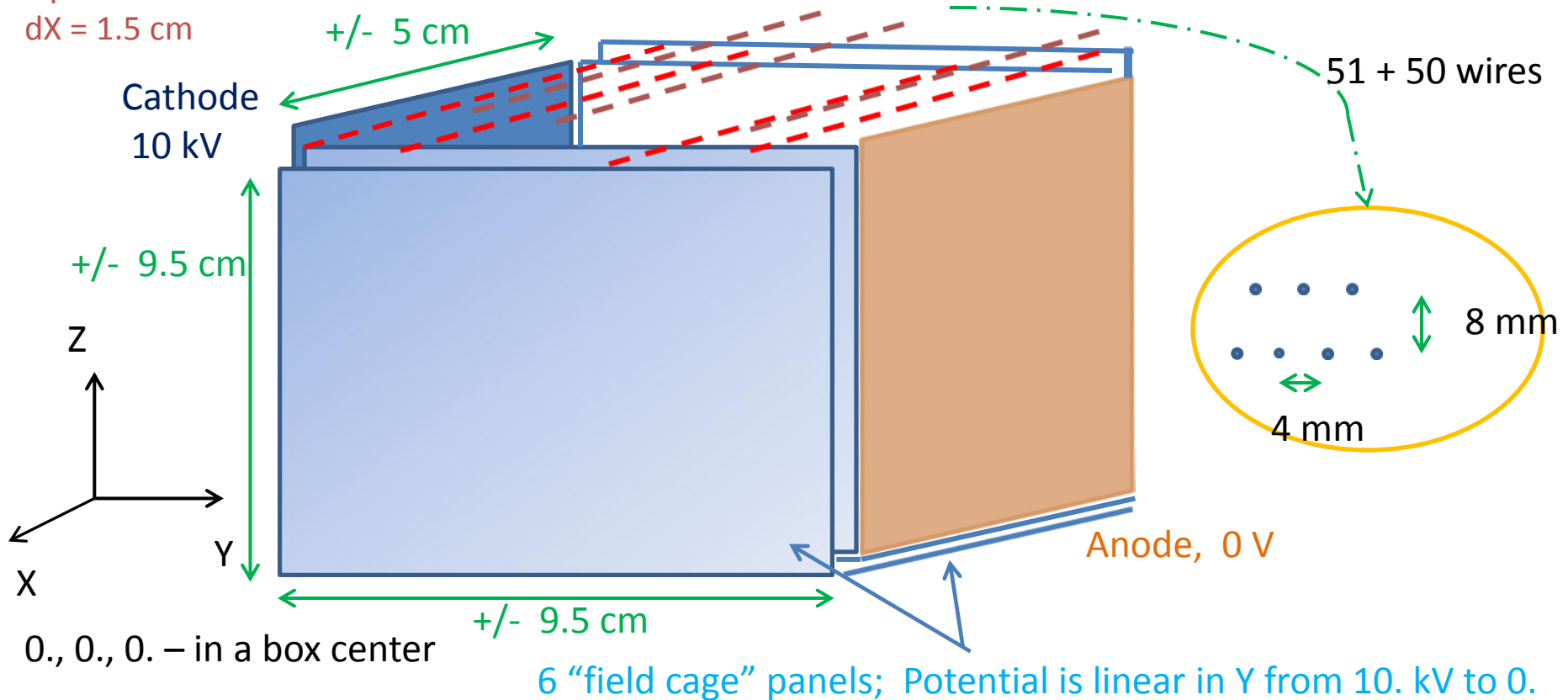
TPC + Ch D cell, small prototype e-static simulation. Amaze-2.0; HiPhi 2.5

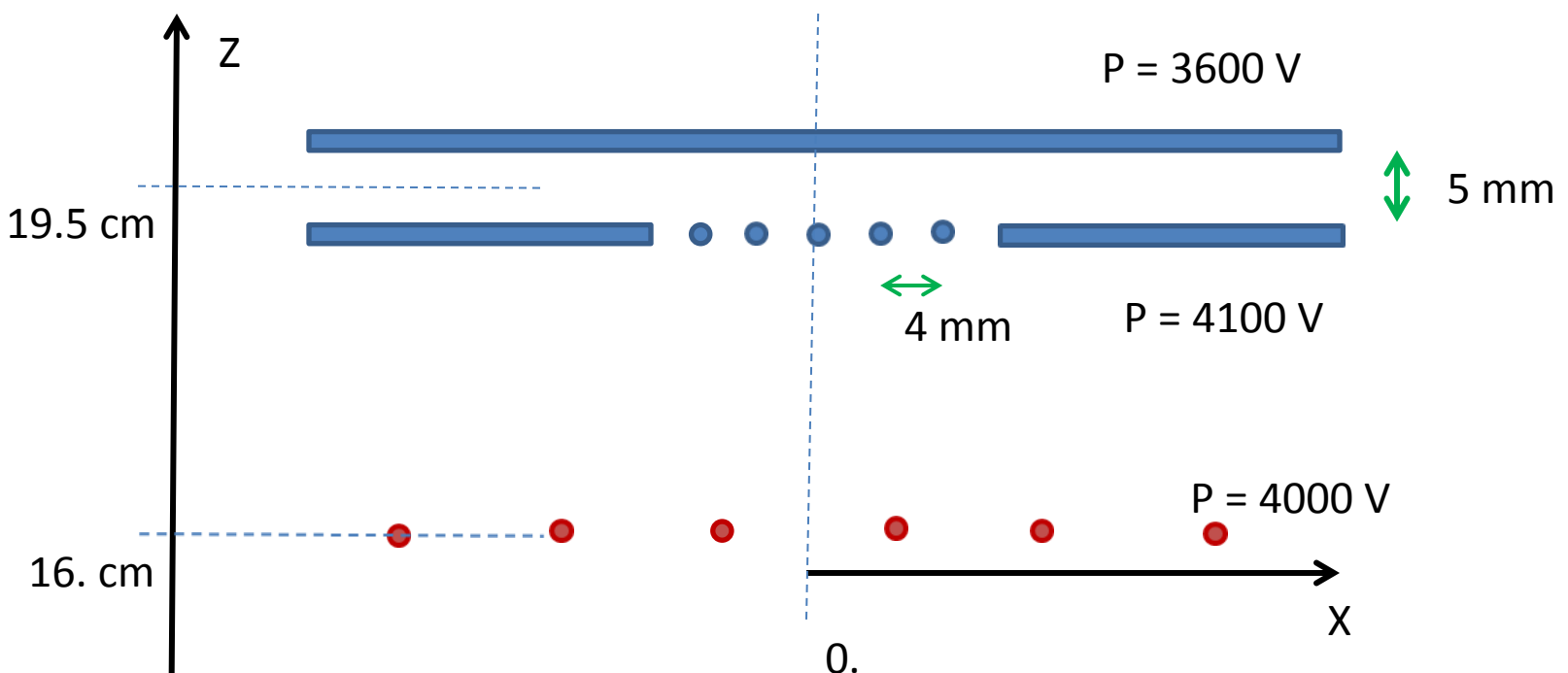
“Ch. D.”; Z pos. = 19 cm.; “dZ” = 8.5 cm  
See next slide for detail

6 field wires; V = 4 kV

Z pos. = 16. cm

dX = 1.5 cm





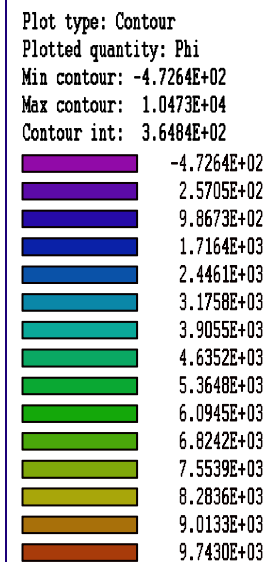
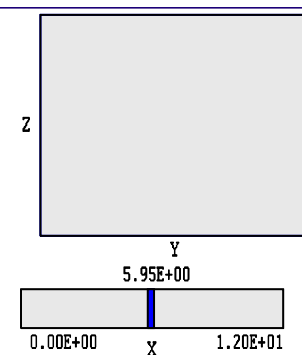
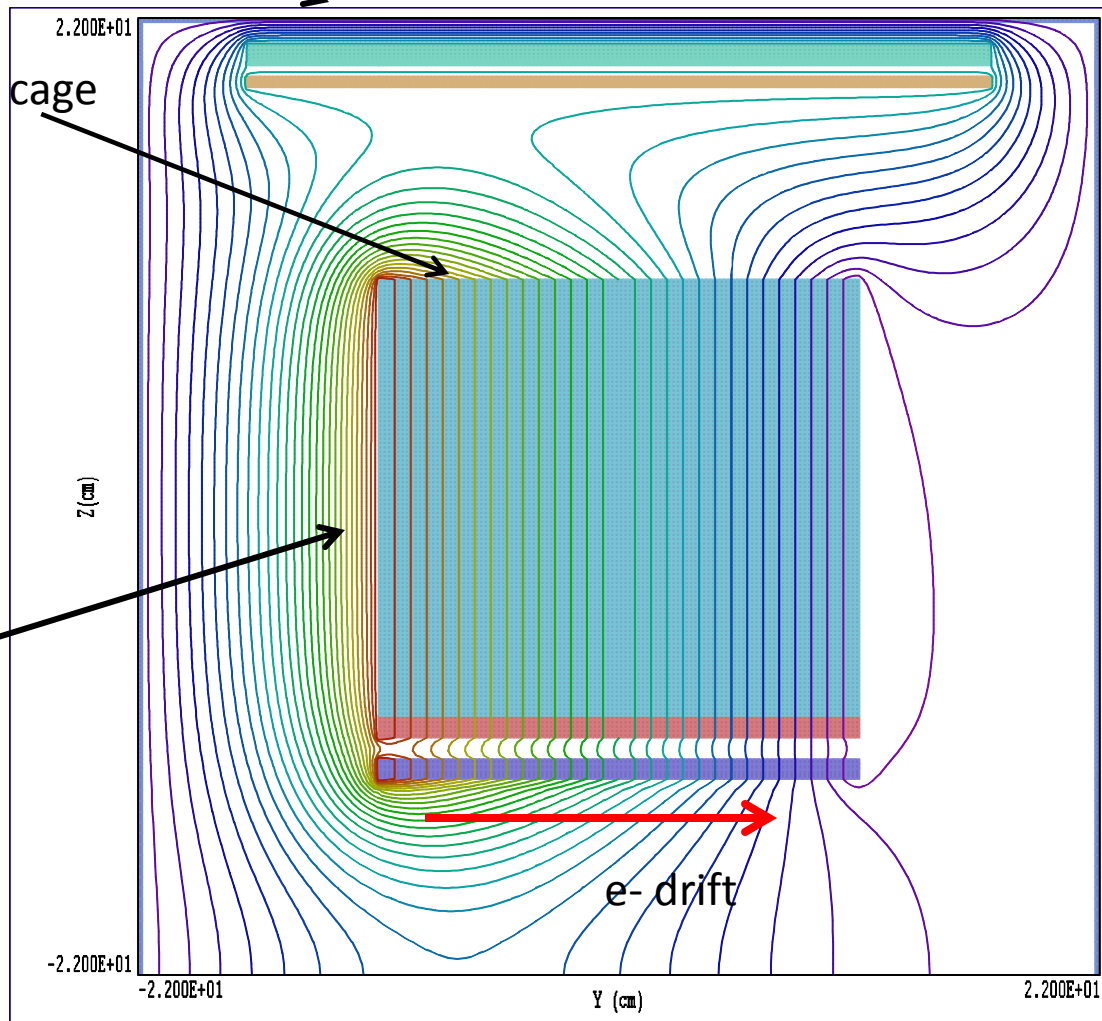
All wires – radius = 200  $\mu\text{m}$

Cherenkov detector

Wires, field cage

Cathode

Z

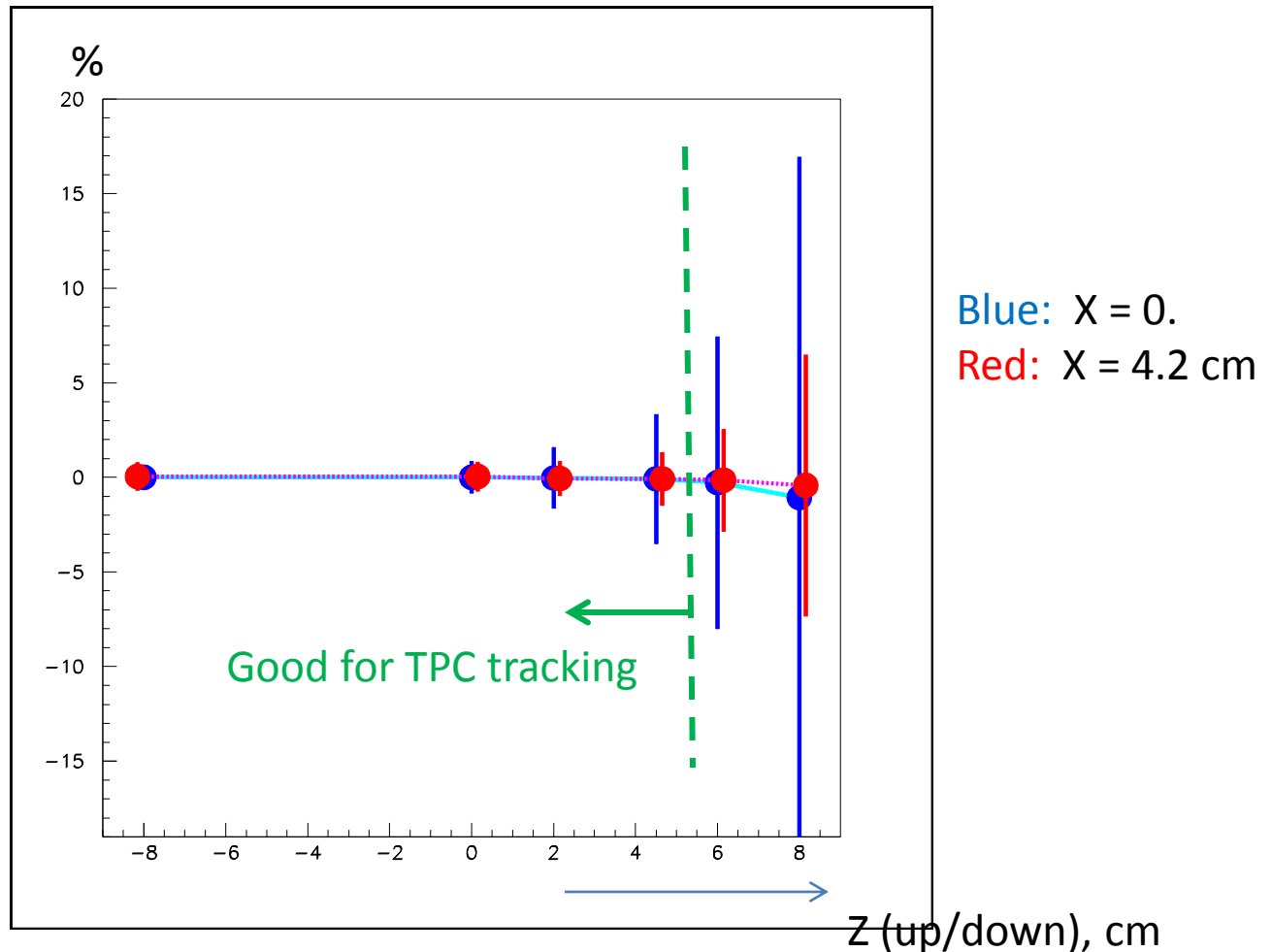


Y X = 0.



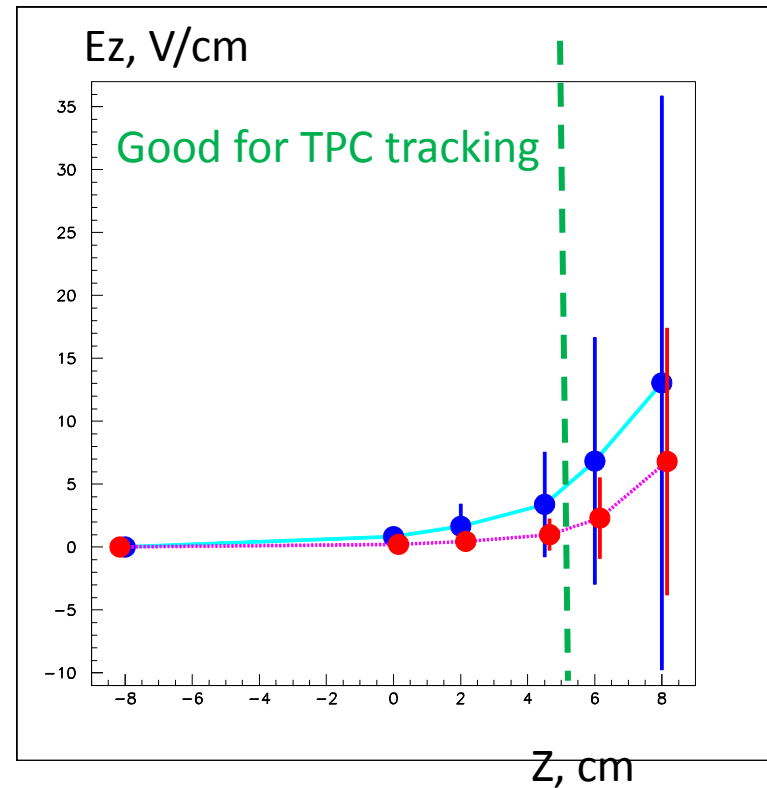
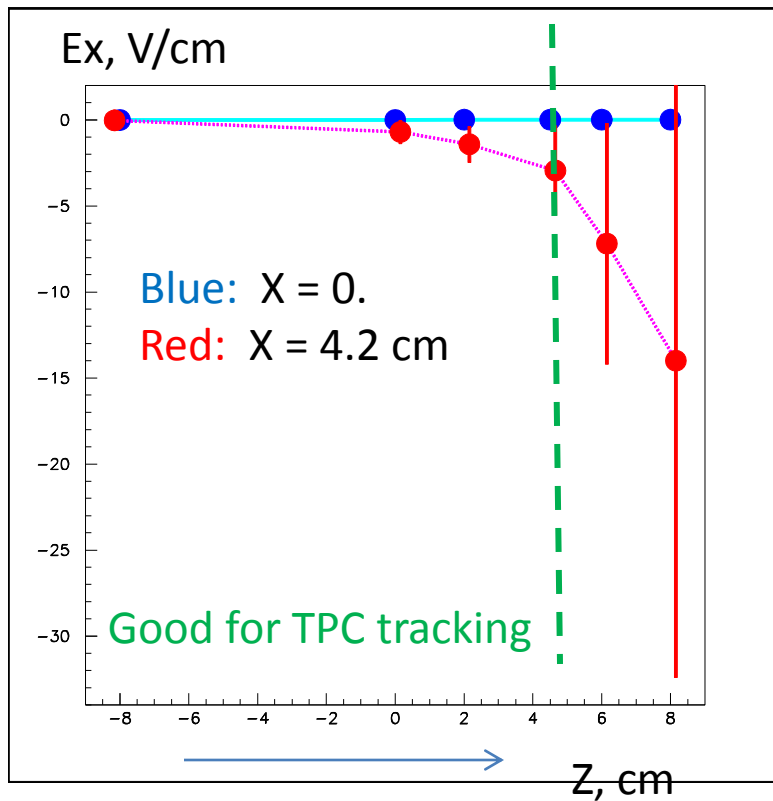
TPC cell. ( $E_y / \langle E_y \rangle - 1$ ) %; Mean and  $\pm$  RMS  
 $\langle E_y \rangle = 499.8$  V/cm

for some Z ( up/down) and X positions and 40 points along Y (drift)



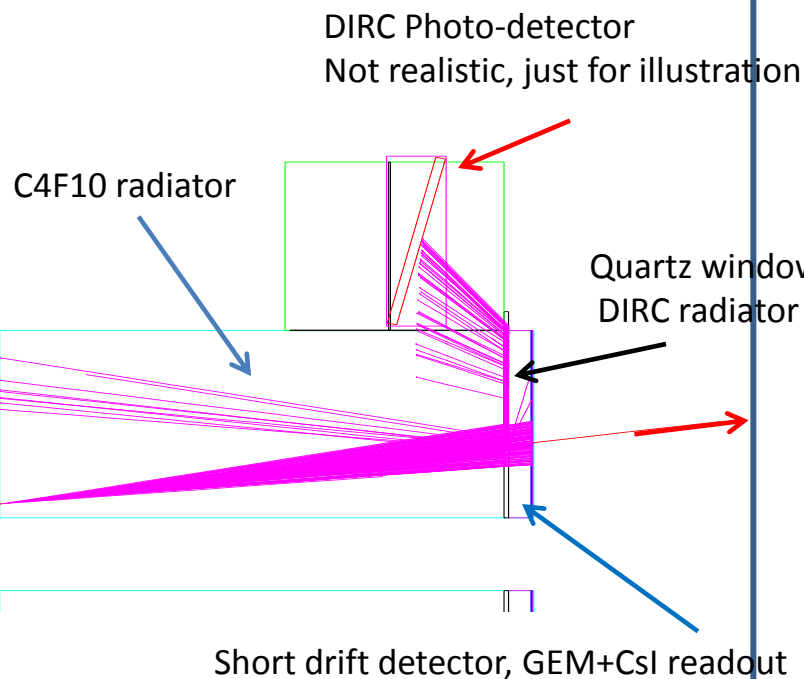
TPC cell.  $E_x$  and  $E_z$  (V/cm) ;

Mean and  $\pm$  RMS for some Z and X positions and 40 points along Y (drift)

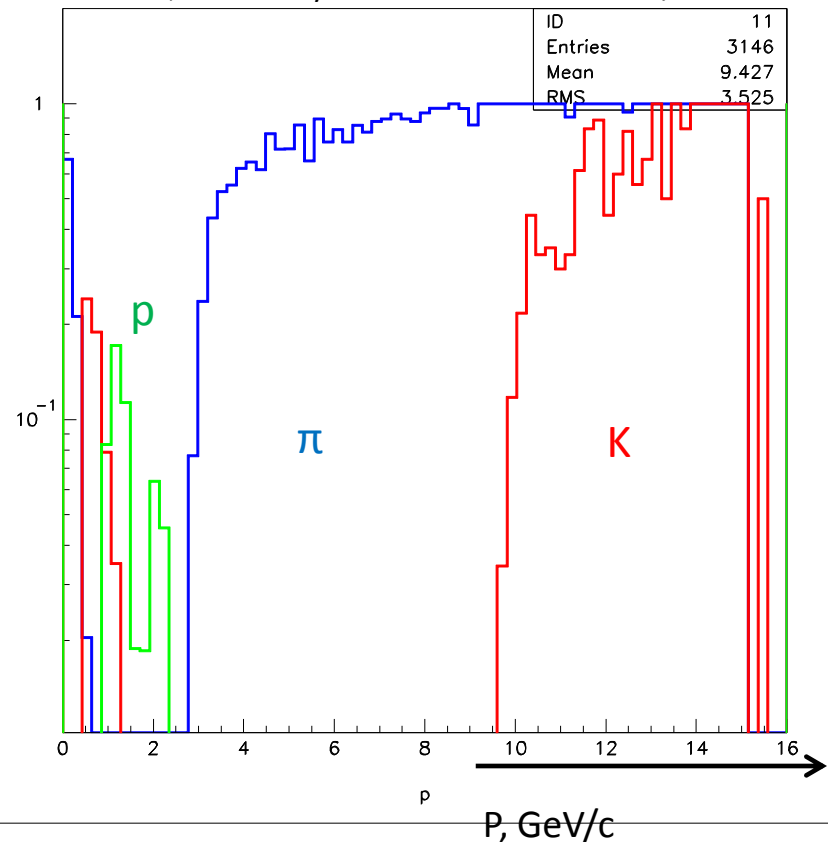


- It is only a “first step” to simulate E-field, and more job should be done (different (more powerful) software)
- Preliminary conclusion:
  - ~5 cm (“down”) from TPC field cage wires → TPC E-field looks “reasonable”.
  - ~10 cm (“up”) from TPC field cage wires → E-field of Cherenkov Detector is OK
- There is a sense to construct and test a prototype.
- This project is in a progress:
  - “special” vessel to move/control Cherenkov Detector (Ch. D.,  $10 \times 10 \text{ cm}^2$ , four GEM foils, 3D-read-out ) distance from TPC; that can be used in a beam-test; and keep in mind that the first GEM foil of (Ch. D.) will be with CsI (in a future, as a second step)
  - $\sim 20 \times 20 \times 10 \text{ cm}^3$  small TPC prototype with wires as a part of field cage on the “top” and with two  $10 \times 10 \text{ cm}^2$  triple GEM, pad readout (it can be only one but will be “moved” up – down)

“three-in-one” Detector in Forward  
Cherenkov + DIRC + SDGD  
Experience from PANDA, including TPC



C4F10+GEM+CsI response simulation; 2d-readout;  
Hadron PiD, Probability to reconstruct >3 UV hits / event

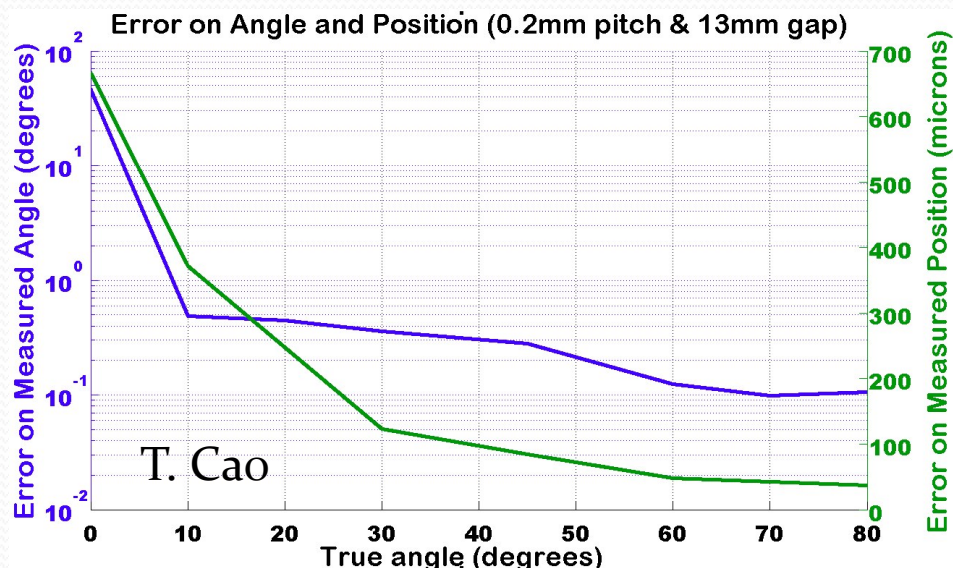




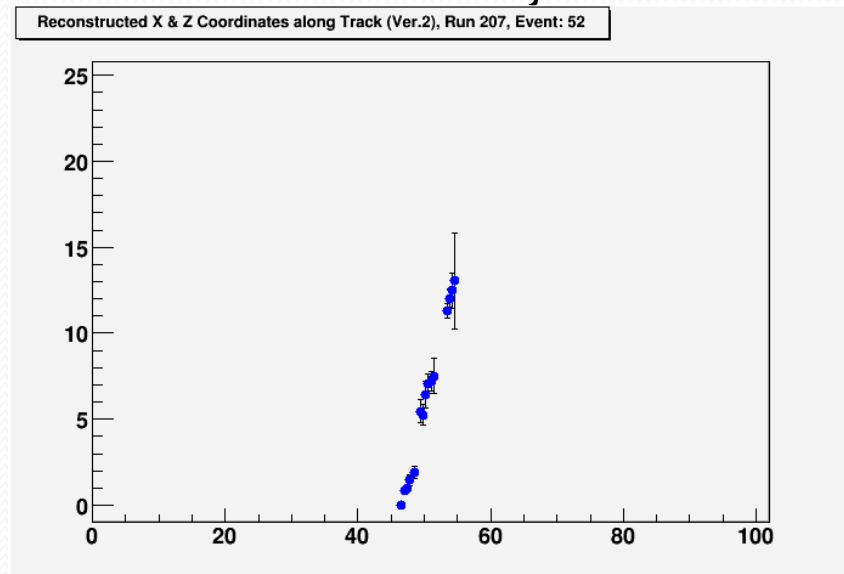
# Back Up Slides

# Quantifying the Limitations of Track Recon.

## MC Results on Track Reconstruction Errors



## Fluctuations in Primary Ionization



- For tracks near zero degrees, less pads fire and the track reconstruction gets more ambiguous, leading to larger errors. Here it is better to rely on the centroid for giving the position of the track, where high gas diffusion is preferable.
- For larger angled tracks, gas diffusion and charge sharing between pads is the major source of error, since the true arrival time of the column of charge above a given pad is distorted → Need gas with low diffusion (CF<sub>4</sub>?).
- Charge fluctuations on the primary ionization lead to small charge clusters, which can be difficult to measure. This can put a limit on the arrival time calculations at each strip.

# ADDITIONAL SUPPORT SLIDE

# Zigzag strips vs. straight strips



	Pitch [mm]	Typical Resolution [μm]
Zigzag strips & analog r/o	2.0	80
Straight strips & binary r/o	0.6	270
Improvement factor w/ zigzag strips	3.3	3.4

Can reduce # of  
readout channels  
(and electronics  
cost) **by 70%** of  
current design

&

Improve resolution  
by factor 3-4

A “**figure of merit**”:  $3.3 \times 3.4 = 11.2$  potential improvement factor

⇒ Potential for **order of magnitude improvement over standard readout design**



- **Objective**

***Develop GEM detectors for EIC forward tracker***

- **Current R&D activities**

- Investigating GEM readout structure with zigzag strips
  - Potential for significant electronics **cost reduction** (3× fewer channels)
  - Constructed two 10cm × 10cm Triple-GEM prototypes
  - Bench tests at Fl. Tech
  - Beam test at CERN SPS
- Completed construction of a 30cm × 30cm “Self-Stretch Sans Spacer” (S4) Triple-GEM detector
  - Features COMPASS-style x-y Cartesian readout board
  - Will investigate gain non-uniformities due to the new construction technique as function of x-y position using the high position sensitivity available with this readout

# University of Virginia EIC detector R&D goals

- Develop techniques to fabricate large area GEM chambers with narrow edges and 2D readout.
- Construct a GEM foil stretcher for large area GEM foils.
- Develop a 2 D readout plane for large area GEM chambers
- Construct a 100 cm x (25-40) cm trapezoidal GEM chamber with narrow edges and 2D readout

## Motivation

- The current design for an EIC detector calls for 2 or 3 ring type GEM detector stations, consisting of trapezoidal GEM modules with radial lengths between 1 -1.5 m.
- GEM modules approaching that size have been developed as part of CMS GEM R&D; however these were of the “self-stretching” GEM type, which requires the foils stretching components to be part of the GEM chamber edge; this significantly increases the amount of material present in the detector volume.
- An alternate approach to use an external stretcher for the GEM foils and to glue the stretched foils on to narrow frames. The proposed UVa GEM prototype is based on this approach and is designed with 8 mm edges, minimizing the amount of material within the detector volume.
- The large area CMS prototype GEM modules had 1D readout; the UVa prototype will have a 2D readout, so that the radial coordinate of the track is available in addition to the azimuthal coordinate

# Current status of R&D efforts

- Constructed a working Mini-Drift tracking detector at BNL, based on 10x10cm GEMs, with a 17mm drift gap.
- Used to reconstruct track segments from charged particle tracks entering the detector. Multiple layers of such a device will provide a sequence of vectors along the particle's trajectory.
- Performed successful bench-top measurements in the lab of low energy tracks from a  $\beta$ -source and cosmic ray tracks--necessary for debugging and the development of a track finding algorithm.
- Developed simulations to estimate the position and angular resolution of the detector, with the given readout pad pcb/electronics, and detector gas used.
- Performed successful beam test at CERN to measure the position and angular resolution as a function of the angle of the incident track.
- Initial test of a possible choice for the readout electronics: VMM1 chip.

## Outlook

- With the aid of our simulation program, we will study other viable options for the readout and the detector gas, followed by real tests of promising candidates for each.
- After further refinements to this detector are made, we plan on producing a larger prototype and conducting more beam tests.

- We have very good connections / participation both ALICE TPC upgrade program and future e+e- collider TPC R&D
- Experience and knowledge from these two projects and PANDA experiment